

Multimedia Channel Allocation in Cognitive Radio Networks using FDM-FDMA and OFDM-FDMA ^{*†}

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Abstract

In conventional wireless systems, unless a contiguous frequency band with width at least equal to the required bandwidth is obtained, multimedia communication can not be effected with the desired Quality of Service. We propose here a novel channel allocation technique to overcome this limitation in a Cognitive Radio Network which is based on utilizing several non-contiguous channels, each of width smaller than the required bandwidth, but whose sum equals at least the required bandwidth. We present algorithms for channel sensing, channel reservation and channel deallocation along with transmission and reception protocols with two different implementations based on *FDM – FDMA* and *OFDM – FDMA* techniques. Simulation results for both these implementations show that the proposed technique outperforms the existing first-fit and best-fit [8, 7] allocation techniques in terms of the average number of attempts needed for acquiring the necessary number of channels for all traffic situations ranging from light to extremely heavy traffic. Further, the proposed technique can allocate the required numbers of channels in less than one second with *FDM – FDMA* (4.5 second with *OFDM – FDMA*) even for 96% traffic load, while the first-fit and best-fit techniques fail to allocate any channel in such situations.

1 Introduction

The concept of *Cognitive Radio (CR)* [28] is based on dividing the available radio spectrum into several parts, with some part reserved for the licensed users and the rest freely available for all. A *Cognitive Radio Network (CRN)* provides the capability of sharing the spectrum in an opportunistic manner by both licensed and unlicensed users, leading to an increase in the effective utilization of the available spectrum. According to a survey conducted by *Federal Communications Commission (FCC)* [13, 14, 12, 4], the usage of the radio spectrum is non-uniform. While some portions of the spectrum are heavily used, other portions remain relatively under-utilized. Thus, when a licensed user is not currently using the spectrum, an unlicensed user can sense this fact and may temporarily use this channel for his/her purpose. However, as soon as the licensed owner starts using his channel, the unlicensed user must relinquish this channel immediately, and move to a different one by sensing the *spectrum holes* or *white spaces*.

A cognitive radio should have the capability of being programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [6, 20]. The transmission parameters, e.g., power level, modulation scheme, etc. of a cognitive radio should be reconfigurable not only at the beginning of a transmission but also during the transmission, when it is switched to a different spectrum band.

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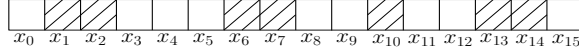


Figure 1: Spectrum Divided into Channels (Unused Channels shown as White)

Of late, there also has been an increasing trend of multimedia communication in the form of voice, text, still image and video in various applications involving *CRN*. Designing efficient algorithms for allocating channels to a large number of such users of *CRNs* and maintaining the *Quality of Service (QoS)* for multimedia communication constitute an important research problem.

1.1 Related Works

Multimedia communication through *CRNs* has already been studied by several authors [28, 24, 29]. Mitola J. first introduced the concept of *flexible mobile multimedia communications* [28] in a *CRN*. Kushwaha et al. [24] used fountain coding for packet generation and conversion to send data with high reliability and tolerable delay. Shing et al. [29] proposed the idea of dynamic channel selection for video streaming over a *CRN*, based on some priority-based scheduling of video signals. On the other hand Lei et. al. worked on spectrum fragmentation by their method “Jello” [34], where they detect “edges” of power spectrum, then use classical best-fit, worst-fit and first-fit algorithm for spectrum selection and finally they do a distributed coordinate procedure to synchronize transceiver system. However, in all of these communication schemes, a video signal can not be communicated over the *CRN* unless a channel of sufficiently large bandwidth for maintaining the *QoS* of these video signals, is allocated from the white spaces of the spectrum. Thus, even if the sum of all the available white spaces in the spectrum may be larger than the required bandwidth for transmitting a video signal, it may not be possible to transmit the video signal if there is no single white space in the spectrum which can provide the required large bandwidth for its communication. Basically, this is a situation of *fragmentation* of the spectrum into small holes, with no hole being large enough to accommodate a video signal transmission. It was mentioned by Akyildiz et al. [5] that “*CR users may not detect any single spectrum band to meet the user’s requirements. Therefore, multiple noncontiguous spectrum bands can be simultaneously used for transmission in CR networks*”. Some authors have addressed this implementation issue of the proposal by using *Orthogonal Frequency Division Multiplexing (OFDM)* - based *CRN* [9, 31]. However, *Multi-Band OFDM (MBOFDM)* system for allowing more than one sender to send their messages in the *CRN* is still a challenging problem [25].

Techniques for detection of unused spectrum and sharing the spectrum without harmful interference with other users with the help of a *Common Control Channel (CCC)* have been presented by Krishnamurthy et al. [23], Masri et al. [26] and Bayhan and Alagöz [8]. The *CCC* is used for supporting the transmission coordination and spectrum related information exchange between the *CR* users. It facilitates neighbor discovery, helps in spectrum sensing coordination, control signaling and exchange of local measurements between the *CR* users. Spectrum sensing without using a *CCC* has been considered by Kondareddy et al. [22] and Xin and Cao [33].

Taxonomy, open issues, and challenges for channel assignment algorithms in a *CRN* have been described in [3]. Allocation schemes can be fixed [2, 27], dynamic [35, 10, 29, 2, 27] or [2, 27] depending on the flexibility of assigning channels to the cells in the network. The dynamic channel allocation in the spectrum is similar to the computer classical memory management strategies like “first-fit”, “best-fit”, and “worst-fit” [36]. Very recently, Bayhan and Alagöz [8, 7] have proposed best-fit channel selection techniques in cognitive radio networks.

1.2 Problem Statement

Consider a representative scenario depicted in Fig. 1 where we show a part of the spectrum divided into 16 channels marked as x_0, x_1, \dots, x_{15} , each of these channels being of the same bandwidth equal to B_{min} which is the minimum bandwidth for a multimedia signal. For example, if the bandwidth requirements for the voice, text and video signals are 64 Kbps, 128 Kbps and 512 Kbps respectively, then B_{min} is taken to be 64 Kbps. Thus, to transmit an audio signal, we need only one channel, while for a video signal, we need eight consecutive channels (x_i ’s). However, as we see from Fig. 1, there is no continuous band consisting of eight channels, but a total of nine channels are still available. We need to devise an appropriate technique to allow the transmission of the given video signal through eight of these available nine channels, without compromising the video quality at the receiving end.

Channel assignment process in a *CRN* may broadly be divided in two subproblems - *channel sensing* and *channel allocation*. We assume that the transmission range of a node is equal to its sensing range. A node U

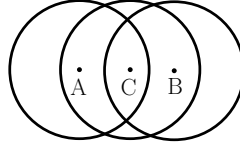


Figure 2: Nodes with their Respective Sensing Regions

is called a 1-distance neighbor of a node V if U falls under the transmission or sensing range of the node V . While sensing, we assume that a node can always sense the channels which are being used by all of its 1-distance neighbors for transmitting their respective data. Referring to Fig. 2, the transmitting channels of all the neighbors at 1-distance from a node A can be sensed by node A . Consider the node C in Fig. 2 which is a 1-distance neighbor of A . Node B is another 1-distance neighbor of C but node B is at 2-distance apart from A . The channels used by C in receiving some information from B , can not be sensed by node A . Thus, node B can give rise to *hidden node problem* [21] while allocating channels to node A . To be more specific, if A and B both want to communicate their messages to C at the same time using the same channel (when both of them independently sense that channel as free), the node C will experience a collision, and thus both the messages will be lost at C . The channel allocation algorithm must address this hidden node problem while allocating channels for the message communication from A to C .

Another problem arises when, node C has a capability of receiving a multimedia signal of bandwidth 512 Kbps as shown in Fig. 2. Node A sends some data to node C which requires only 128 Kbps bandwidth. Now, node B also wants to send some data to node C at the same time which requires, say, 384 Kbps bandwidth. With the existing *OFDM* technique [32] in *CRN*, we can not transmit data simultaneously to the node C from node A and node B , though node C might have the capacity to handle the data, unless there is a sufficient gap between the channels used for two different pairs of communicating nodes to avoid channel interference. According to Mahmoud et al. [25], the *MBOFDM* system to handle such situation is a challenging problem due to synchronization requirement between the transmitter and the receiver.

We consider the situation for multimedia communication in which a typical user may require varying number of channels. Thus, a particular node may sometimes need just one single channel and sometimes a number of channels to communicate its messages depending on the types of the multimedia signals and their required *QoS*.

1.3 Our Contribution

In this paper, we propose an elegant way of overcoming the problem of fragmentation of the available spectrum as mentioned in Section 1.2, with regard to the communication of multimedia signals over the *CRN*, while maintaining the *QoS* requirement. We propose a technique for establishing a communication between sender and receiver nodes for single hop communication of multimedia data, where we first decompose a multimedia signal in time domain in terms of a number of bit-sets, with each set containing sufficiently sparsely bits so as to be transmitted over just a single channel of bandwidth B_{min} and yet maintaining the signal quality. Thus, the total information content of a signal during a particular time frame is basically divided into several packets, with each packet being transmitted through one available channel in the white space. The constituent packets generated for a given time frame may, however, be transmitted over non-contiguous channels. At the receiver end, all the packets received through these channels will be used for reconstructing the original signal without degrading the signal quality.

Using the above strategy, we propose here a novel channel allocation technique which assigns non-contiguous channels for effecting multimedia communication between a sender and a receiver very fast through a random number generation process, so that the channel fragmentation problem as experienced in conventional first-fit or best-fit techniques is completely overcome resulting in very high channel utilization with negligible overhead in time. Detailed description of the proposed scheme is given below.

To allow multiple senders for sending their data simultaneously through the *CRN*, we propose two possible channel allocation techniques, one based on *Frequency Division Multiplexing (FDM)* and *Frequency Division Multiple Access (FDMA)* (*FDM – FDMA*) and another based on *OFDM* and *FDMA* (*OFDM – FDMA*). For the *FDM – FDMA* allocation, we use the non-overlapping channels, where the channel width is assumed to be large enough to include the guard band, as shown in Fig. 3(a). Here, the basic idea is to use *FDM* for every pair of communicating nodes, but *FDMA* for different pairs of communicating nodes. Referring to Fig. 2,

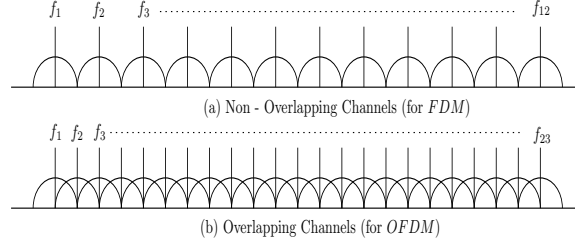


Figure 3: Channels configuration

while the channels for communication between two nodes A and C are allocated using FDM and the channels for communication between nodes B and C are also allocated using FDM , the channel allocation for the pairs (A, C) and (B, C) follows the $FDMA$ technique. For the $OFDM - FDMA$ allocation, we use the overlapping orthogonal channels, as shown in Fig. 3(b). Here, the basic idea is to use $OFDM$ for every pair of communicating nodes, but $FDMA$ for different pairs of communicating nodes. To avoid inter-channel interferences we have to maintain certain minimum gap between every pair of channels allocated to different nodes. Referring to Fig. 2, while the channels for communication between two nodes A and C are allocated using $OFDM$ and the channels for communication between nodes B and C are also allocated using $OFDM$, the channel allocation for the pairs (A, C) and (B, C) follows the $FDMA$ technique. Thus, we have to maintain certain minimum gap between every pair of channels allocated to nodes A and B to avoid inter-channel interferences. We present algorithms for channel sensing, channel reservation and channel deallocation avoiding the hidden node problem and also avoiding possible collision with the channel demands from other users of the CRN . Corresponding transmission and reception protocols are also proposed.

We theoretically analyze our proposed algorithms to predict the average number of iterations or attempts made by our proposed algorithm for allocating the channels. In our later discussions, we use the terms *iterations* and *attempts* interchangeably throughout the text. The average number of such attempts is $O(1/f)$, where f is the fraction of the free or available channels. In dynamic channel allocation, first-fit and best-fit techniques are commonly used ones [8, 7, 34, 19, 38, 37], and thus in our simulation, we compare our proposed protocol with first-fit and best-fit techniques for channel allocation. Simulation results show that the average number of attempts for acquiring the required number of channels agrees well to the theoretical values even for extremely heavy traffic with about 96% blocked channels. From simulation, we also see that the proposed technique always outperforms the existing first-fit and best-fit [8, 7] allocation techniques in terms of the average number of attempts needed for acquiring the necessary number of channels for all traffic situations ranging from light to extremely heavy traffic. The proposed technique can allocate the required numbers of channels in less than a second time with $FDM - FDMA$ even for 96% traffic load and in less than 4.5 sec with $OFDM - FDMA$ for 99% traffic load, while the first-fit and best-fit techniques fail to allocate any channel in such situations. We can intuitively explain why our proposed technique performs better than the first-fit and best-fit techniques. Actually, both the latter techniques suffer from the channel fragmentation problem and channels cannot be allocated unless a contiguous free band of required number (DN) of channels is found. In contrast to this, our proposed technique removes the requirement of a single contiguous free band containing all these DN channels and thus, the success rate is 100% with our technique even with an extremely heavy traffic load when the existing approaches fail to allocate the channels. Moreover, because we are exploring the free channels through a random number generation process and every time we get a free channel, we include that one for our purpose, leads to a quick termination of our allocation algorithm with a success.

2 Basic Ideas of our Proposed Protocol

2.1 Creating Small Bandwidth Cognitive Sub-Data Channels

Consider a band-limited signal having a bandwidth of, say W . Let us assume that the signal is sampled with a sampling frequency of $2W$. Referring to Fig. 4, let s_0, s_1, \dots, s_{N-1} be N samples taken over the time period T of the band-limited signal at a sampling interval of $\tau = \frac{1}{2W}$. Thus, $T = N\tau$. Let us assume that from every sample, we get b bits. Thus, the total number of bits is Nb . So, the bits generated from all N samples are $b_0, b_1, \dots, b_{Nb-1}$. Let the bandwidth W of this signal be less than or equal to nB_{min} . We then partition the Nb

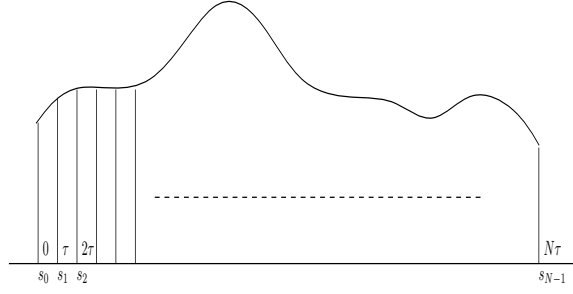


Figure 4: Samples from the signal

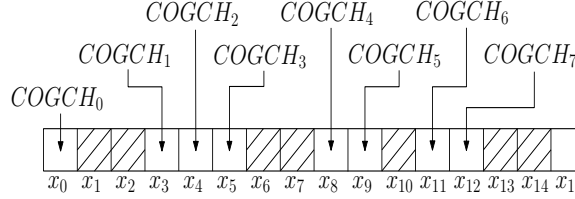


Figure 5: Utilized Spectrum with small bandwidth Cognitive Channels

bits in n subsets $BS_0, BS_1, BS_2, \dots, BS_{n-1}$, where the bit-set BS_i is defined as,

$$BS_i = \{b_j | j = i \mod n, 0 \leq i, j \leq n-1\} \quad (1)$$

Note that in each of these BS_i 's, the bits are separated by $n\tau$ time, and hence, these would require a transmission bandwidth of $\frac{W}{n} \leq B_{min}$. Thus, to transmit the original signal as shown in Fig. 4, we search for the availability of n channels each of bandwidth B_{min} in the white space of the spectrum.

Let $COGCH_i, i = 0, 1, \dots, n-1$ be these n cognitive channels such that the bits in the bit-set BS_i is transmitted through $COGCH_i$ (as shown in Fig. 5 for $n = 8$). In practice, corresponding to each time frame of a suitable duration T , we take the bits in the bit-set BS_i to form a data sub-packet SP_i . The header of each such sub-packet will contain the identity of the time frame (e.g., in the form of a packet number PN) as well as its *Sub-Packet Number* (SPN) equal to i . At the receiving end, all these received sub-packets having the same packet number will be used to reconstruct the original transmitted signal.

2.2 Physical Implementation

2.2.1 Physical Implementation of FDM – FDMA

We assume that all *CR* users are *Secondary Users* (*SUs*) and have the same priority. Similarly, all *Primary Users* (*PUs*) are assumed to have the same priority which is greater than that of a *SU*. We also assume that any given node in the system has the maximum capability of providing some *DN* (*Demand Number*) channels. Thus, a node A may be allowed to be involved in simultaneously communicating more than one signal, so long as the sum of the numbers of channels used by it in communicating all these signals is less than or equal to DN . For example, voice (64 Kbps), data (128 Kbps), still image (256 Kbps), video (384 Kbps) and online streaming (512 Kbps) needs DN as 1, 2, 4, 6 and 8, respectively, as we assume that B_{min} is 64 Kbps. We assume the presence of a dedicated *CCC* [23, 26, 8] operating on a specific frequency (f_{CCC}) for coordination between the various *SUs*, with the communications through *CCC* effected in discrete time slots. For a low traffic load, communication through *CCC* can be done by following either *IEEE 802.11 CSMA/CA* [15, 30] protocol. However, under moderate to heavy traffic, one may use any conventional *controlled access* [15, 30] method like *Bit-Map* [15, 30] protocol to improve the performance. If, we use *Bit-Map* protocol then each attempt made by our algorithm requires $O(\Delta)$ time, where Δ is the maximum node degree of the network.

The block diagrams of the proposed *FDM – FDMA* transmitter and receiver have been shown in Figs. 6(a) and 6(b), respectively. In this scheme, for every channel we need a separate modulator and demodulator system. The *CCC* channel, through which the control messages are transmitted, is totally separated from the data channels. The block *Splitter*, in Fig. 6(a), is working as a demultiplexer by which the BS_i can be created, leading

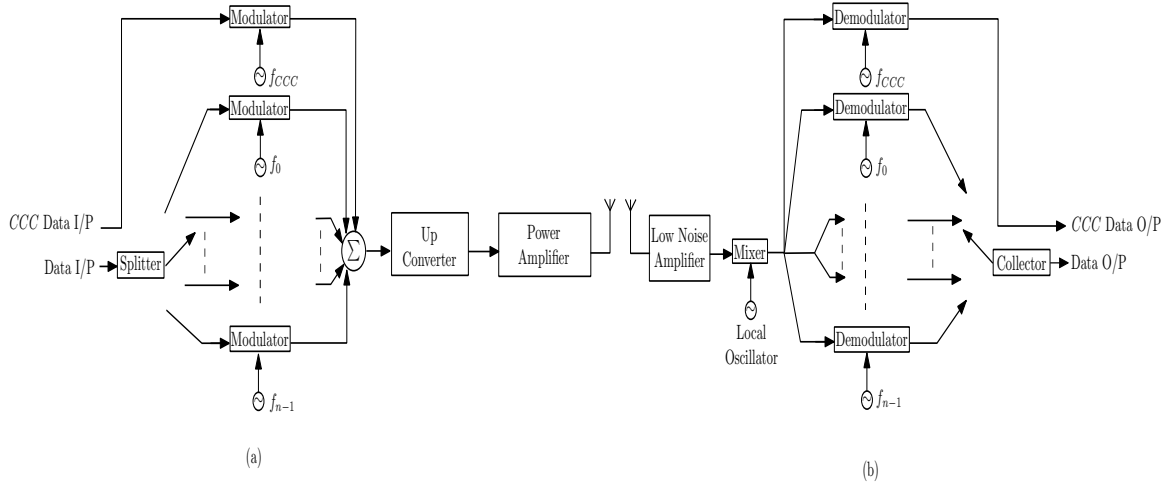


Figure 6: (a) *FDM – FDMA* Transmitter Block Diagram, (b) *FDM – FDMA* Receiver Block Diagram

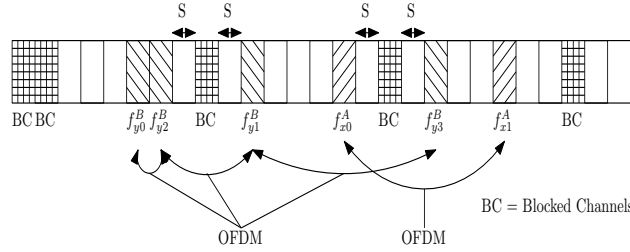


Figure 7: Channel allocation for node *A* and node *B* in overlapping channel

to generation of sub-packets SP_i . On the receiver side, the *Collector* in Fig. 6(b), is used to gather bits from different channels to form the packet constituted from the bits corresponding to all the BS_i s, which is required for regeneration of the multimedia data. Each $COGCH_i$ works on different frequencies f_i 's. For *FDM – FDMA* technique, we can select all the frequencies f_i 's in non-overlapping channel (as shown in Fig. 3(a)). An alternative scheme using commercially available *MIMO* system can also be used depending on the relative cost and ease of implementation.

2.2.2 Physical Implementation of *OFDM – FDMA*

For *OFDM – FDMA* technique, the frequency f_i 's can be selected in such a way that all the f_i 's are orthogonal [32] leading to *OFDM* modulation for one node which requires more than one channel to transmit its data, and the other nodes are to select free channels in such a way as to maintain certain minimum gap between two consecutively chosen channels to avoid inter-channel interference for different nodes in overlapping channels (as shown in Fig. 3(b)). As an example, referring to Fig. 2, nodes *A* and *B* need 2 and 4 channels respectively, to transmit some data to node *C*. Thus, node *A* selects frequencies f_{x0}^A and f_{x1}^A for transmitting its data, while node *B* selects frequencies f_{y0}^B , f_{y1}^B , f_{y2}^B and f_{y3}^B for its communication purpose as shown in Fig. 7. Here, the carriers operating at f_{x0}^A and f_{x1}^A are orthogonal to each other and similarly f_{y0}^B , f_{y1}^B , f_{y2}^B and f_{y3}^B are also orthogonal to each other, but f_{x0}^A and f_{x1}^A need to be separated with some minimum band gap of S (as shown in Fig. 7) from the frequencies f_{y0}^B , f_{y1}^B , f_{y2}^B and f_{y3}^B to facilitate the synchronization process in the two destined receivers. Furthermore, to maintain the needed orthogonality condition between the *OFDM* channels, all the *OFDM* carriers need to be synchronously related to a unique pilot carrier, which can be transmitted (from some select nodes playing the role of collaborating leaders) in the same *OFDM* band periodically over time. The frequency of the pilot carrier should be placed conveniently in the *OFDM* frequency range (but not used by any node for data transmission). We, however, assume that this sacrifice of one single *OFDM* carrier for the pilot in the entire *OFDM* transmission bandwidth will not impact the spectral efficiency of the system at large. Every node will synthesize its own *OFDM* carriers from the pilot carrier. In effect this will imply that, the *OFDM* carrier

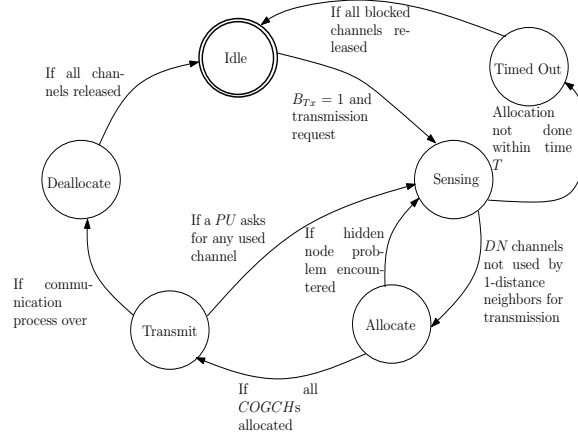


Figure 8: State diagram

frequencies transmitted from all the nodes and the pilot carrier frequency should be integrally related to a lower carrier frequency, which would be a highest common factor for all of them. This will lead to some additional hardware for the nodes along with the *IFFT/FFT*-based *OFDM* generation and demodulation schemes with arbitrary but small number (DN) of *OFDM* carriers. However, we consider this additional hardware complexity to be realizable with today's *VLSI* design techniques and worthwhile as well keeping in mind the benefits that one would be able to derive in respect of the spectral efficiency achievable from this proposition.

2.3 State Diagram of the Overall System

In Fig. 8 we draw a state diagram that explains the basic functional units of the communication system as depicted through its various states and the state transition arcs. We start from the *Idle* state. When the transmitter buffer of a node becomes full, a status bit B_{Tx} of the node is set to 1 (which is otherwise 0). When $B_{Tx} = 1$ and this node wants to transmit, it moves from the *Idle* state to the *Sensing* state. The node in this *Sensing* state explores the availability of free channels of the required number DN as demanded by the multimedia signal to be transmitted by the node. If it finds DN number of channels not being used by any of its 1-distance neighbors for transmission, then it blocks these channels temporarily and moves to *Allocate* state. In *Allocate* state, it determines whether there is any hidden node problem. If not, then it goes on to the *Transmit* state, otherwise it moves back to the *Sensing* state. In the *Sensing* state, the node maintains a clock to measure the time needed for sensing and allocation of the required number DN of channels. When the nodes first enters the *Sensing* state from the *Idle* state, the clock and the timing register both are set to 0. The timing register is updated by the clock whenever the node moves from the *Allocate* to *Sensing* state. If allocation of channels is not done within a specified time-out period T , then the node moves to *Timed Out* state, at which it releases all the blocked channels, if any, and goes back to the *Idle* state. In the *Transmit* state, the node transmits its message through the allocated DN channels. When the transmission is complete, it goes to *Deallocate* state where it releases all these DN number of blocked channels, resets B_{Tx} to 0 and goes back to the *Idle* state. While the node is in the *Transmit* state, if any primary user *PU* reports, asking for any of the channels used by this node, then those channels will be immediately released and the system will go back to the *Sensing* state, setting again both the clock and the timing register to 0.

3 Proposed Protocol

3.1 Algorithm for Connection Establishment

Let SA and DA denote the addresses of the source node and the destination node, respectively. To establish a communication link the source node SA needs to sense and allocate DN number of channels for transmitting the multimedia signal using *CCC*. We consider below the connection establishment process for multimedia signals to be executed by the source node SA and the destination node DA .

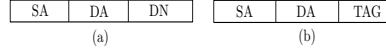


Figure 9: (a) *CM* message and (b) *ACK* or *WAIT* message

1. Sense the channels not being used by *A*'s 2-distance neighbors (to avoid the hidden node problem) as shown in Fig. 2. This would be effected with the help of some control and acknowledgement messages communicated through the *CCC*.
2. Allocate the *DN* free channels found above to the destination node *C* so that it becomes ready for receiving the desired multimedia signal from *A*.

The above steps of allocating channels to any source-destination pair would be done *dynamically* in a *distributed manner* with the help of the *CCC*. After this allocation process, the actual multimedia communication between a source-destination pair will continue unless some or all of these channels are deallocated due to the arrival of one or more primary users.

3.1.1 Reservation of Channel

The node *SA* transmits a *Control Message (CM)* with *SA*, *DA* and *DN* values as shown in Fig. 9(a). After sending this control message, it waits up to some maximum time-out period, say δ_T , for getting either an *Acknowledgement (ACK)* message or a *WAIT* message from *DA*, both of which would contain the *SA* and *DA* values, with one more *TAG* bit, as shown in Fig. 9(b), which is set to '0' for an *ACK* message and '1' for a *WAIT* message. The *ACK* message is sent if node *DA* is capable of providing *DN* number of channels for receiving the multimedia signal from *SA* (i.e., when the available number of channels *AN* at *DA* is greater than or equal to *DN*, while the *WAIT* message is sent when $AN \leq DN$.) Since the node *DA* may simultaneously receive such channel reservation requests from other source nodes as well, for $AN \geq DN$, it temporarily reserves the requested number (i.e., *DN*) of channels for node *SA* on a first-come-first-serve basis (without bothering about which *DN* channels). If the node *DA* is not capable of allocating the requested *DN* number of channels to *SA*, then along with sending the *WAIT* message to the node *SA*, it puts this request from *SA* (in the form of *CM*) in a waiting queue for later servicing. If neither the *ACK* nor the *WAIT* message is received by *SA* within δ_T time (due to a possible collision caused by the simultaneous transmission of messages from some other node(s) within 1-distance from *SA* or due to the hidden node problem, i.e., due to a collision at the node *DA* caused by messages from some node, say *V* which is at 1-distance from *DA*, but at 2-distance from *SA*), then *SA* retransmits its control message *CM*. This process of retransmission is repeated by *SA* until an *ACK* or *WAIT* message is received from *DA*. The algorithms *reserve_channels_transmitter* and *reserve_channels_receiver* to be executed by nodes *SA* and *DA* are given in Algorithm 1 and 2 respectively.

Algorithm 1: *Reserve_Channels_Transmitter*

Input: *SA*, *DA* and *DN*
Output: channels_reserved

```

1 channels_reserved = false;
2 while channels_reserved = false AND  $B_{Tx} = 1$  do
3   Transmit CM to the node DA;
4   Wait for  $\delta_T$  time to receive ACK or Wait Signal;
5   if ACK or WAIT Signal received within  $\delta_T$  then
6     if ACK is received within  $\delta_T$  then
7       channels_reserved = true;
8     else
9       Wait for ACK from DA /* WAIT received */;
10    channels_reserved = true;

```

3.1.2 Sensing and Allocation of Channels

Sensing and Allocation of Channels for *FDM – FDMA* Technique After getting the *ACK* message from the destination node *DA* in reply to the *CM* message as described in Section 3.1.1, the source node *SA* will try to find the required *DN* number of data channels from the currently available white spaces of the spectrum. This will be done by randomly choosing a set of *DN* distinct channels which are not being used by any of the 2-distance

Algorithm 2: Reserve_Channels_Receiver

Input: CM (consisting of SA , DA and DN)
Output: ACK , $WAIT$ to the Transmitter

```

1 if  $AN \geq DN$  then
2    $AN = AN - DN$ ;
3   Update its database;
4   Transmit  $ACK$ ;
5 else
6   Enter  $CM$  in a waiting queue;
7   Send back  $WAIT$  Signal to node  $SA$ ;

```

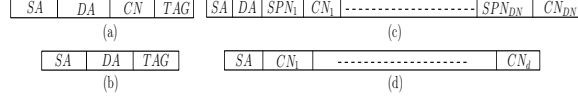


Figure 10: (a) TAM or CCB message, (b) TAM_ACK or $NACK$ message, (c) $CHALLOC$ message and (d) CRM message ($d = |channel_set|$)

neighbors of SA for transmission as well as reception (to avoid the hidden node problem) of data. We assume that the width of the non-overlapping channel already includes the bandgap to avoid inter-channel interference and hence, a free channel for a node U means one which is not being used by any other node within the 2-distance neighborhood of U . We randomly generate a number i and then sense whether channel i is free (with respect to all nodes in 2-distance neighborhood of U). If channel i is free, then it can be allocated to U . In fact, we generate DN such random numbers and sense in parallel whether all the channels corresponding to these randomly generated DN numbers are free. If m free channels are found by this process, then the process terminates if $m = DN$; otherwise the whole process is repeated to find the required number $m - DN$ of free channels to be allocated to U . Each iteration of this loop is termed as an *attempt*, as introduced earlier in Section 1.3.

The fact that none of the 1-distance neighbors of SA is currently using a given channel for transmitting their data, can easily be determined by listening to this channel by SA (channel sensing). However, to avoid the hidden node problem, whether a given channel is being used by any node U among the 1-distance neighbors of SA for receiving some messages from some node, say V , which is at 2-distance from SA , can not be determined by such channel sensing. To decipher that, node SA has to send a *Trial Allocation Message* (TAM) to all of its 1-distance neighbors which would contain the source and destination addresses (i.e., SA and DA) along with the *Channel Number* (CN) in question. The structure of the TAM message is as shown in Fig. 10(a), where the TAG field is set to '0' for a TAM . On getting this TAM , a node U would send back an acknowledgement (TAM_ACK) or a no-acknowledgement ($NACK$) message to SA depending on whether U is currently not using the channel CN for receiving any message or not, respectively. The TAM_ACK and $NACK$ messages are of the form as shown in Fig. 10(b), where the TAG field is set to '00' for a $NACK$ and '01' for an TAM_ACK . Node U can check this fact efficiently if it maintains a channel usage database in the form an *AVL tree* as shown in Fig. 11 where each node of the tree contains a tuple (CN, SA) and insertion or finding an element in the tree is done based on the CN field only. The choice of *AVL tree* as the data structure for this purpose enables us insertion, deletion and finding an element from it all in $O(\log m)$ time where DN is the total number of nodes in this tree. In case U is currently not using the channel CN for receiving any message, it temporarily allocates the channel CN to the node SA and keeps this information by inserting a new node with this CN and SA information in the *AVL tree*. This would help prohibiting other nodes selecting this channel CN for transmitting their data when

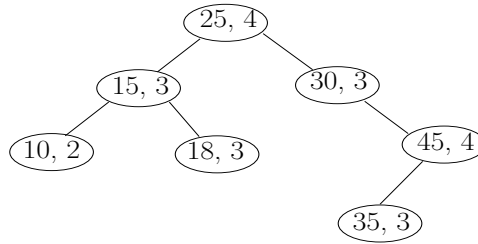


Figure 11: *AVL tree* for storing the channel usage status of a node

the node SA is still in the process of selecting all of its required channels and has not yet completed that process. If SA does not receive any $NACK$ message within a maximum time-out period δ_T from any node in reply to this TAM message, then SA puts this channel number CN in its chosen set of channels $channel_set$; otherwise, SA can not use the channel CN for transmitting its data and hence it broadcasts a *Clear Channel Blockage (CCB)* message to all of its 1-distance neighbors. The structure of the CCB message is same as that of a TAM shown in Fig. 10(a), where the TAG field is set to '1' for a CCB . If a node U receives this CCB message, then U will delete the corresponding node from its AVL tree storing its channel usage status (thus, the channel CN will now be treated as available by the node U).

The above process of allocating channels for SA will be repeated to get all DN channels after which the transmission will be started. When the required number of channels are found through the above process, a *Channel Allocate (CHALLOC)* command is broadcast by SA to its 1-distance neighbors with the information regarding the destination node DA , and the sub-packet number (SPN) of every packet along with the allocated channel number (CN) as shown in Fig. 10(c). On receiving this $CHALLOC$ command, node DA will record the information regarding the SPN and CN for the sub-packets to be received from SA in its channel reservation database, while any other node will release the temporary blockage of the corresponding channel numbers. If, however, the required number of channels are not found within a maximum time unit, say T ($\delta_T \ll T$), then the node SA can not start its transmission at the moment and it broadcasts a *Channel Release Message (CRM)* signal of the form as shown in Fig. 10(d), to all of its 1-distance neighbors to release temporarily blocked channels. Node SA has to try again for getting the required DN number of channels until success or the transmitter buffer becomes 0. The algorithms *Sense_Allocate_Transmitter_FDM – FDMA* and *Sense_Allocate_Receiver* to be executed by the node SA and any other receiving node are given in Algorithm 3, and 4, respectively.

Algorithm 3: *Sense_Allocate_Transmitter_FDM – FDMA*

```

Input:  $DA, DN, MAX$ 
Output: Selected channel numbers  $c_1, c_2, \dots, c_{DN}$ 
1  $channel\_set = \emptyset$ ;
2  $cardinality = 0$  / *  $cardinality = |channel\_set| * /$ ;
3  $j = DN$ ;
4  $time = 0$ ;
5 while  $time \leq T$  do
6   Randomly generate a set of  $j$  distinct channel numbers  $c_1, c_2, \dots, c_j$  in the range 1 to  $MAX$  such that for  $1 \leq i \leq j$ ,  $c_i \notin channel\_set$ ;
7   Sense channel numbers  $c_1, c_2, \dots, c_j$  in parallel /*to check if channel  $c_i$  is idle*/;
8   for  $i = 1$  to  $j$  do
9     if  $|channel\_set| < DN$  then
10      if channel  $c_i$  idle then
11        Form the  $TAM$  message with  $CN = c_i$ ;
12         $trial\_no\_TAM = 1$ ;
13         $flag = true$ ;
14        while ( $trial\_no\_TAM < Max\_trial\_TAM$  AND  $flag$ ) do
15          Broadcast the  $TAM$  message to all 1-distance neighbors using the  $CCC$ ;
16          Wait up to a maximum time of  $\delta_T$  to receive reply message(s);
17          if reply received then
18             $flag = false$ ;
19            if no  $NACK$  received then
20               $channel\_set = channel\_set \cup \{c_i\}$ ;
21               $cardinality = cardinality + 1$ ;
22            else
23              Send  $CCB$  with  $CN$ ;
24          else
25             $trial\_no\_TAM = trial\_no\_TAM + 1$ ;
26       $time = time + 1$ ;
27 if  $DN = cardinality$  then
28   Broadcast  $CHALLOC$  command formed with the  $channel\_set$  to all 1-distance neighbors;
29 else
30   Broadcast  $CRM$  formed with the  $channel\_set$  to all 1-distance neighbors to release all temporarily blocked channels;

```

Sensing and Allocation of Channels for OFDM – FDMA Technique Node SA has to send a *Trial Allocation Message (TAM)* to all of its 1-distance neighbors which would contain the source and destination addresses (i.e., SA and DA) along with the *Channel Number (CN)* in question. The structure of the TAM message is as shown in Fig. 10(a), where the TAG field is set to '0' for a TAM . On getting this TAM , a node U would send back an acknowledgement (TAM_ACK) or a no-acknowledgement ($NACK$) message to SA depending on whether U is currently not using the channel CN for receiving any message or not, respectively. The TAM_ACK and

Algorithm 4: Sense_Allocate_Receiver

Input: $TAM, CHALLOC$
Output: Select and locked data channels.

```
1 /* The following code will be executed by all nodes receiving the TAM and CHALLOC messages*/;  
2 if TAM received with source node SA and channel number CN then  
3   if channel CN is free for its 1-distance neighbor AND CN is not temporarily blocked for any other node then  
4     Update its channel usage database by temporarily marking channel number CN as being used by node SA;  
5     Transmit TAM_ACK to SA through CCC;  
6   else  
7     Transmit NACK to SA through CCC;  
8 if CHALLOC received then  
9   if DA in CHALLOC = its own id then  
10    Update its channel reservation database with SPN and CN values assigned from CHALLOC for each channel;  
11   else  
12    Update its channel usage database by releasing the temporarily blocked channel numbers indicated in CHALLOC;  
13 if CRM received then  
14   Update its channel usage database by releasing the temporarily blocked channel numbers indicated in CRM;
```

Algorithm 5: Sense_Allocate_Transmitter_OFDM – FDMA

Input: DA, DN, MAX
Output: Selected channel numbers c_1, c_2, \dots, c_{DN}

```
1 channel_set =  $\emptyset$ ;  
2 j = DN;  
3 time = 0;  
4 flag1 = true;  
5 required_channel_numbers = DN;  
6 while time  $\leq T$  AND flag1 do  
7   temp_set =  $\emptyset$ ;  
8   Randomly generate a set of j distinct channel numbers  $c_1^1, c_2^1, \dots, c_j^1$  in the range 1 to MAX such that for  $1 \leq i \leq j$ ,  $c_i^1 \notin channel\_set$ ;  
9   for k = 1 to j do  
10     $c_k^2 = c_k^1 + 1$ ;  
11     $c_k^3 = c_k^1 + 2$ ;  
12   Create a list of  $3 \times DN$  numbers with  $c_1^1, c_1^2, c_1^3, \dots, c_j^1, c_j^2, c_j^3$ ;  
13   Sense channel numbers  $c_1^1, c_1^2, c_1^3, \dots, c_j^1, c_j^2, c_j^3$  in parallel /*to check if channel  $c_i^1, c_i^2, c_i^3$  is idle*/;  
14   for i = 1 to j do  
15     for k = 1 to 3 do  
16       if channel  $c_i^k$  idle then  
17         Form the TAM message with  $CN = c_i^k$ ;  
18         trial_no_TAM = 1;  
19         flag2 = true;  
20         while (trial_no_TAM < Max_trial_TAM AND flag2) do  
21           Broadcast the TAM message to all 1-distance neighbors using the CCC;  
22           Wait up to a maximum time of  $\delta_T$  to receive reply message(s);  
23           if reply received then  
24             flag2 = false;  
25             if no NACK received then  
26               temp_set = temp_set  $\cup \{c_i^k\}$ ;  
27             else  
28               Send CCB with CN;  
29           else  
30             trial_no_TAM = trial_no_TAM + 1;  
31   find_free_bands(temp_set, required_channel_numbers, channel_set);  
32   if required_channel_numbers = 0 then  
33     flag1 = false;  
34   time = time + 1;  
35 if DN = |channel_set| then  
36   Broadcast CHALLOC command formed with the channel_set to all 1-distance neighbors;  
37 else  
38   Broadcast CRM formed with the channel_set to all 1-distance neighbors to release all temporarily blocked channels;
```

Algorithm 6: *procedure find_free_bands*

Input: *temp_set*, *required_channel_numbers*;
Output: *required_channel_numbers*, *channel_set*

- 1 Sort *temp_set* in non-increasing order;
- 2 Scan *temp_set* to form *band_set* with the 2-tuple (*band_length*, *start_channel_number*) as its element ;
- 3 Set $t \leftarrow |band_set|$;
- 4 Sort *band_set* in non-increasing order of *band_length* component of its elements (2-tuples) ;
- 5 **for** $i = 1$ to t **do**
- 6 **if** *band_set*[*i*].*band_length* > 3 **then**
- 7 $channel_set = channel_set \cup \{band_set[i].start_channel_number + 1, \dots, band_set[i].start_channel_number + band_set[i].band_length - 2\}$;
- 8 $temp_number = \min[DN, band_set[i].start_channel_number + band_set[i].band_length - 2]$;
- 9 $required_channel_numbers = required_channel_numbers - temp_number$;
- 10 **return**(*required_channel_numbers*, *channel_set*);

NACK messages are of the form as shown in Fig. 10(b), where the *TAG* field is set to '00' for a *NACK* and '01' for an *TAM_ACK*. Node *U* can check this fact efficiently if it maintains a channel usage database in the form an *AVL* tree as shown in Fig. 11 where each node of the tree contains a tuple (*CN*, *SA*) and insertion or finding an element in the tree is done based on the *CN* field only. The choice of *AVL* tree as the data structure for this purpose enables us insertion, deletion and finding an element from it all in $O(\log m)$ time where *DN* is the total number of nodes in this tree. In case *U* is currently not using the channel *CN* for receiving any message, it temporarily allocates the channel *CN* to the node *SA* and keeps this information by inserting a new node with this *CN* and *SA* information in the *AVL* tree. This would help prohibiting other nodes selecting this channel *CN* for transmitting their data when the node *SA* is still in the process of selecting all of its required channels and has not yet completed that process. If *SA* does not receive any *NACK* message within a maximum time-out period δ_T from any node in reply to this *TAM* message, then *SA* puts this channel number *CN* in its chosen set of channels *channel_set*; otherwise, *SA* can not use the channel *CN* for transmitting its data and hence it broadcasts a *Clear Channel Blockage (CCB)* message to all of its 1-distance neighbors. The structure of the *CCB* message is same as that of a *TAM* shown in Fig. 10(a), where the *TAG* field is set to '1' for a *CCB*. If a node *U* receives this *CCB* message, then *U* will delete the corresponding node from its *AVL* tree storing its channel usage status (thus, the channel *CN* may now be treated as available by the node *U*).

We assume that a free overlapping channel to be used by a node *U* refers to a channel which is i) not being used by any node within the 2-distance neighborhood of *U* and ii) sufficiently separated from those channels which are being used by all nodes in the 2-distance neighborhood to avoid inter-channel interference. We assume a gap of one channel on either side of the channel to be used by *U* to avoid this interference. Thus, if channel *i* is to be allocated to *U*, then channels $i - 1$, *i* and $i + 1$ must not be used by any node in the 2-distance neighborhood of *U*. However, it can be generalized and we assume that with *OFDM* communication, a contiguous set of *m* channels, $1 \leq m \leq DN$ may be allocated to a node *U*, provided we find a set of $m + 2$ contiguous channels which are not being used by any of the nodes in the 2-distance neighborhood of *U*. Thus, if none of the channels $i - 1, i, \dots, i + m$ are being used by any node in the 2-distance neighborhood of *U*, then the *m* channels $i, i + 1, \dots, i + m - 1$ can be used by *U* in the *OFDM* mode. After randomly generating *i*, we sense whether channels *i*, $i + 1$ and $i + 2$ are free (with respect to all nodes in 2-distance neighborhood of *U*). We mark all these free channels. Here also, we generate *DN* such random numbers and sense in parallel whether all the channels corresponding to these randomly generated *DN* numbers are free, and mark all these free channels found by this step. After this, we check the status of all channels to find a consecutive band of *m* free channels, $3 < m < DN + 2$, out of which $(m - 2)$ consecutive channels may be allocated to *U*. If $m - 2 = DN$, then the process is terminated; otherwise, the whole process is repeated for finding the $m - 2 - DN$ channels still to be allocated to *U*. As with *FDM - FDMA* implementation, one iteration of this loop is termed as an *attempt*. Thus, the sensing time per attempts in *OFDM - FDMA* channel allocation technique is three times more than that in *FDM - FDMA* channel allocation technique.

The detailed steps for finding free bands after getting the free channel numbers have been presented in the *procedure find_free_bands* (Algorithm 6). First, the free channels numbers are included in a set *temp_set* which is then sorted in non-increasing order. This sorted *temp_set* is then scanned once from left to right to produce a set *band_set* containing the 2-tuples (*band_length*, *start_channel_number*) as its elements. This set *band_set* is then sorted in non-increasing order based on the *band_length* field of each 2-tuple. Finally, this sorted *band_set* is scanned once from largest to smallest *band_length* to collect the free bands with largest possible sizes to form the *channel_set*. Since the number of elements in *temp_set* is small (less than $3 \times DN$), the total time for executing this procedure will be very small.

SA	DA	SPN _i	CN _i	TAG
----	----	------------------	-----------------	-----

Figure 12: *DATA_ACK* message

SA	DA	CN ₁	CN _l
----	----	-----------------	-------	-----------------

Figure 13: *CLS* message

The above process of allocating channels for *SA* will be repeated to get all *DN* channels after which the transmission will be started. When the required number of channels are found through the above process, a *Channel Allocate (CHALLOC)* command is broadcast by *SA* to its 1-distance neighbors with the information regarding the destination node *DA*, and the sub-packet number (*SPN*) of every packet along with the allocated channel number (*CN*) as shown in Fig. 10(c). On receiving this *CHALLOC* command, node *DA* will record the information regarding the *SPN* and *CN* for the sub-packets to be received from *SA* in its channel reservation database, while any other node will release the temporary blockage of the corresponding channel numbers. If, however, the required number of channels are not found within a maximum time unit, say T ($\delta_T \ll T$), then the node *SA* can not start its transmission at the moment and it broadcasts a *Channel Release Message (CRM)* signal of the form as shown in Fig. 10(d), to all of its 1-distance neighbors to release temporarily blocked channels. Node *SA* has to try again for getting the required *DN* number of channels until success or the transmitter buffer becomes 0.

The algorithm *Sense_Allocate_Transmitter_OFDM – FDMA* to be executed by the node *SA* and any other receiving node are given in 5.

3.2 Algorithms for Transmission and Reception

When all the required *DN* channels are allocated to both the nodes *SA* and *DA*, the node *SA* starts transmission of its multimedia data following the algorithm *Transmit_Data_Packet* given below. The receiving node *DA* will execute the algorithm *Receive_Data_Packet* described below to receive the *DN* sub-packets corresponding to each sub-packet number *SPN* and will reconstruct the original message from these sub-packets. If a sub-packet is received correctly by *DA*, then an acknowledgement message (*DATA_ACK*) will be sent by *DA* back to *SA*. The structure of the *ACK* message is as shown in Fig. 12. If *DATA_ACK* is not received within time out period δ_T , then node *SA* has to sense if a primary user has started using his channel. Then it immediately relinquishes this channel. *SA* will then look for some other alternative channel which can be allocated for transmitting the corresponding data sub-packet. If this is not possible in an extreme situation with a maximum number of trials, say *maxtrial*, then the node *SA* has to abort the transmission. The algorithms *Transmit_Data_Packet* and *Receive_Data_Packet* to be executed by nodes *SA* and *DA* are given in Algorithms 7 and 8 respectively.

3.3 Algorithm for Deallocation of Channels

After successful transmission of all of its data packets, the transmitting node *SA* will release all the data channels used by it (by deleting the corresponding entries from its *AVL* tree storing the channel usage status). Also it issues a channel release message clear signal (*CLS*) of the form shown in Fig. 13 through *CCC*. The receiving node *DA* release all data channels used by node *DA* for this communication (update *AVL* tree) and update its *AN*. All other 1-distance neighbors are also deleting the corresponding entries from its *AVL* tree storing the channel usage status. In case the node *SA* has to abort a transmission, it releases all the channels allocated to both *SA* and *DA* in the same way. When one or more channels used by the node *DA* are released, the next channel reservation request from its waiting queue is considered if that can be satisfied. The waiting queue can be implemented using a linked list with *INFO* field of each node containing the 2-tuple (*SA*, *DN*). However, sensing these waiting requests in a *First-Come-First-Serve (FCFS)* order may result in a poor utilization of the channels. Instead, some other variants of this servicing policy may be chosen to increase the channel utilization. For example, the request from a node with the minimum number of required channels from amongst those waiting for the service may be chosen. This would increase the channel utilization, but in turn, may lead to starvation (similar to *Shortest-Job-First (SJF)* CPU scheduling in operating systems [1]) of the requests with a large value of *DN*. This problem of starvation may, however, be avoided by taking into account the ageing factor of the accumulated requests, resulting into an increased channel utilization with no starvation. The algorithms *Deallocate_Data Channels_Transmitter* and

Algorithm 7: Transmit_Data_Packet

Input: DN , $channel_set$, packet to be transmitted, $maxtrial$
Output: Transmitted packets

```
1  $abort = false$ ;  
2  $PN = 0$ ;  
3 while  $B_{Tx} = 1$  AND  $abort = false$  do  
4   for  $i = 0$  to  $DN - 1$  do  
5     Form the sub-packet  $SPN_i$  with packet number =  $PN$ ,  $sub\_packet\_number = i$ ;  
6      $sub\_packet\_received[i] = false$ ;  
7   forall  $COGCH_i$ ,  $0 \leq i \leq (DN - 1)$ , in parallel do  
8      $trial\_number = 1$ ;  
9     while  $trial\_number \leq maxtrial$  AND  $sub\_packet\_received[i] = false$  do  
10      Transmit the sub-packet  $SPN_i$  through the channel  $COGCH_i$ ;  
11      if  $DATA\_ACK$  received within the time out period  $\delta_T$  then  
12         $sub\_packet\_received = true$ ;  
13      else  
14        Sense if  $PU$  uses this channel;  
15        if  $PU$  uses this channel then  
16          Release this channel and look for another available channel using Algorithm 3 ( $FDM - FDMA$ ) or 5 ( $OFDM - FDMA$ );  
17          if a new channel number  $new\_channel$  is found then  
18             $COGCH_i = new\_channel$ ;  
19             $trial\_number = 1$ ;  
20            /*re-transmission of  $sub\_packet[i]$  is started on this  $new\_channel$  */  
21       $trial\_number = trial\_number + 1$ ;  
22    if  $sub\_packet\_received = false$  then  
23       $abort = true$ ;  
24     $PN = PN + 1$ ;
```

Algorithm 8: Receive_Data_Packet

Input: Received Packet from Transmitter
Output: $DATA_ACK$ messages to the transmitting node SA

```
1 /* to be executed by the receiving node  $DA$  */;  
2 forall  $COGCH_i$ ,  $0 \leq i \leq (DN - 1)$ , in parallel do  
3   if packet received correctly with packet number  $PN$  then  
4     Send  $DATA\_ACK$  message to the transmitting node  $SA$  with packet number  $PN$  and sub-packet number  $i$ ;
```

Deallocate_Data Channels_Receiver to be executed by the node *SA* and *DA* are given in Algorithms 9 and 10 respectively.

Algorithm 9: Deallocate_Data Channels_Transmitter.

Input: Transmission completion signal
Output: Deallocation of all channels

```

1 if data transmission completed then
2   Set  $B_{Tx} = 0$ ;
3 for  $COGCH_i \mid (0 \leq i \leq n-1)$  do
4   Transmits  $CLS$  to all 1-distance neighbors through  $CCC$ ;
5   Release all data channels;
```

Algorithm 10: Deallocate_Data Channels_Receiver.

Input: CLS from transmitter
Output: Deallocation of all channels

```

1 for  $COGCH_i \mid (0 \leq i \leq n-1)$  do
2   if  $CLS$  received then
3     Release all data channels;
4   if  $DA$  in  $CLS = its\ own\ id$  then
5     Update  $AN$ ;
6     Process the waiting queue;
```

4 Performance Analysis

4.1 Performance of Channel Allocation Algorithm using *FDM – FDMA* Technique

Let C be the total number of channels out of which we assume that π channels are in the primary band and the rest are in the secondary band. At any time instant t , let $B_{p,t}$ and $B_{s,t}$ be the numbers of blocked (already allocated by 2-distance neighbors and maintain certain minimum gap between two consecutively chosen channels to avoid inter-channel interference for different nodes) channels in the primary band and the secondary band, respectively. Thus, the total number of blocked channels at time t is given by $B_t = B_{p,t} + B_{s,t}$. Let $F_{p,t}$ be the number of free channels in the primary band at time t , which is given by $\pi - B_{p,t}$. Similarly, let $F_{s,t}$ be the number of free channels in the secondary band at time t , which is given by $C - \pi - B_{s,t}$. Let $F_t = F_{p,t} + F_{s,t}$. Let there be a request at time t for allocating n channels to communicate a given multimedia signal. Referring to Algorithm 3, we try to reserve the required number of channels, i.e., n channels in successive attempts, where each attempt corresponds to a single execution of steps 5 to 26. Assuming that the availability of the F_t free channels can be uniformly distributed over the total spectrum, the probability of getting i , $0 \leq i \leq n$, free channels out of n channels chosen at random follows hypergeometric distribution and is given by $\frac{\binom{F_t}{i} \binom{C-F_t}{n-i}}{\binom{C}{n}}$. The expected number of free

channels over all possible situations is then given by $\sum_{i=0}^n \frac{i \binom{F_t}{i} \binom{C-F_t}{n-i}}{\binom{C}{n}} = \sum_{i=1}^n \frac{F_t \binom{F_t-1}{i-1} \binom{C-F_t}{n-i}}{\binom{C}{n}} = \frac{F_t \binom{C-1}{n-1}}{\binom{C}{n}} = nf$,

where $f = \frac{F_t}{C}$. Thus, on an average, the number of reserved channels by the first attempt is equal to nf . When all channels are free, $f = 1$ and all the required n channels are reserved in the first attempt. If $f < 1$, then the remaining number of channels to be allocated after the first attempt is $n - nf = n(1 - f)$, on an average. For the second attempt, since $F_t - nf$ is the number of free channels, the success probability for getting a free channel will again be a hypergeometric distribution, leading to $nf(1 - \frac{n}{C})$ channels reserved by the second attempt on an average. Thus, on an average, after the second attempt, the total number of reserved channels is $\min\{n, nf + nf(1 - \frac{n}{C})\}$ and the number of channels yet to be allocated is $n - \{nf + nf(1 - \frac{n}{C})\}$. Generalizing this observation, we have the following result.

Lemma 1. *The expected number of channels reserved during the $(k + 1)^{th}$ attempt, $k \geq 0$, is $nf(1 - \frac{kn}{C})$. Also, on an average, the total number of channels reserved after the k^{th} attempt is $\min(n, nkf)$.*

Proof : We prove the result by induction. From the discussion above, the proposition that *at the k^{th} attempt, the number of channels reserved is $nf\{1 - \frac{(k-1)n}{C}\}$ on an average*, is true for $k = 1$ and 2. Let us assume that this proposition is true for $k = k$.

Table A-1: All possible cases about the status of three consecutive channels

Status of c_k^1	Status of c_k^2	Status of c_k^3	Probability of selecting c_k^2 and c_k^3 as free	Number of free channels
0	0	0	f^2	3
0	0	1	$f \cdot (1 - f)$	2
0	1	0	$f \cdot (1 - f)$	1
0	1	1	$(1 - f)^2$	1
1	0	0	f^2	2
1	0	1	$f \cdot (1 - f)$	1
1	1	0	$f \cdot (1 - f)$	1
1	1	1	$(1 - f)^2$	0

Hence, at the $(k + 1)^{th}$ attempt, the expected number of channels reserved is equal to $\frac{n(F_t - [nf + nf(1 - \frac{n}{C}) + \dots + nf\{1 - \frac{(k-1)n}{C}\}])}{C} \approx nf(1 - \frac{kn}{C})$.

Hence, on an average, the total number of channels reserved after the k^{th} attempt is $\min[n, \{nf + nf(1 - \frac{n}{C}) + nf(1 - \frac{2n}{C}) + \dots + nf(1 - \frac{(k-1)n}{C})\}] \approx \min(n, nkf)$. \square

Theorem 1. To reserve n channels, the required number of attempts, on an average, is equal to $\lceil \frac{1}{f} \rceil$.

Proof: By lemma 1, the total number of channels reserved after k^{th} attempt is $\min(n, nkf)$, on an average. Hence, if α is the minimum number of attempts required for reserving all the n channels, then $nf\alpha \geq n$, i.e., $\alpha \geq \frac{1}{f}$, on an average. Hence the theorem. \square

Remark 1. Theorem 1 basically establishes that more the number of free channels, less is the average number of attempts for acquiring the required numbers of channels.

Corollary 1. On an average, reservation of all n channels can be done in $\psi = \lceil \frac{1}{f} \rceil \zeta + O(1)$ time, where ζ is the time for a single execution of the loop in the channel allocation algorithm.

It may be noted that, if we use *Bit-Map* [15, 30] protocol for communication through *CCC*, then ζ is $O(\Delta)$ time, where Δ is the maximum node degree of the network as already mentioned in Section 2.2.

4.2 Performance of Channel Allocation Algorithm using OFDM – FDMA Technique

In order to evaluate the theoretical performance of the Algorithm 5, let us assume that we try to reserve n channels in successive attempts, where each attempt corresponds to a single execution of steps 6 to 34 of the algorithm. We first generate n random numbers c_k^1 , $1 \leq k \leq n$. Note that c_k^1 is one of the n channels chosen at random in which the probability that i channels will be free is given by the hypergeometric distribution as in the case of *FDM – FDMA* allocation. However, in Algorithm 5, we also check whether the two adjacent channels $c_k^2 = c_k^1 + 1$ and $c_k^3 = c_k^1 + 2$ are free. There can be eight different possibilities regarding the status of these three channels as depicted in Table A-1, where an entry is '0' if the corresponding channel is free, and '1' if it is blocked. Note that the probability that the channel $c_k^1 + 1$ or $c_k^1 + 2$ will be free, is given by $\frac{F_t}{C} = f$. Table A-1 shows the probability of selections of c_k^2 and c_k^3 in each of the eight possible situations with the corresponding number of free channels found.

From Table A-1, given that the channel c_k^1 is free, the expected number of free channels selected out of these three consecutive channels is given by $3f^2 + 2f(1 - f) + f(1 - f) + (1 - f)^2 = f^2 + f + 1$. Similarly, given that the channel c_k^1 is blocked, the expected number of free channels selected out of these three consecutive channels is given by $2f^2 + 2f(1 - f) = 2f$. Thus, the expected number of free channels over all possible situations is given by,

$$\sum_{i=0}^n i \cdot (f^2 + f + 1) \frac{\binom{F_t}{i} \binom{C-F_t}{n-i}}{\binom{C}{n}} + \sum_{i=0}^n (n-i) \cdot 2f \frac{\binom{F_t}{i} \binom{C-F_t}{n-i}}{\binom{C}{n}} = n(3f - f^2 + f^3) \approx 3nf, \text{ when } f \ll 1.$$

Thus, in a heavy traffic condition, when f is very small, the average number of attempts to reserve the required number of channels made by Algorithm 5 is approximately equal to $\lceil \frac{1}{3f} \rceil$.

5 Simulation of Channel Allocation Algorithm

In this section, we show the results of simulating our proposed protocol, and evaluate its performance in terms of the average number of attempts made by the proposed algorithm for acquiring the required number of channels to communicate a given multimedia signal and also in term of success rate. We also compare our proposed protocol with first-fit and best-fit channel allocation techniques. Simulations are performed 10,000 times on

Table A-2: Average number of blocked channels by 2-distance neighbors with different values of range

Range in meter	Number of Blocked Channels										
	100 Nodes	200 Nodes	300 Nodes	400 Nodes	500 Nodes	600 Nodes	700 Nodes	800 Nodes	900 Nodes	1000 Nodes	1100 Nodes
10	9	32	55	79	104	129	153	178	203	229	254
15	33	82	133	184	237	288	340	392	444	497	549
20	62	143	227	312	397	481	565	652	736	819	905
25	96	212	334	453	571	689	811	927	1048	1166	1283

Table A-3: Average number of free channels for 500 and 700 nodes in Non-Overlapping Channel

Average number of blocked channels	Average number of free primary channels (F_P)	Average number of free secondary channels (F_S)	Average number of free channels (F)
For 500 nodes			
254	307	439	746
387	252	361	613
547	187	266	453
721	115	164	279
For 700 nodes			
303	287	410	697
490	210	300	510
715	117	168	285
961	16	23	39

random network topologies with each of 100 to 1100 nodes, in which nodes are distributed randomly within an area of $(100 \times 100)m^2$. The number of channels required by a node for communication is also varied from 1 to 8. We assume that, the signal to be sent has a mix of different multimedia signal types with the proportion of 50%, 20%, 15%, 10% and 5% for voice, data, still image, video and online streaming data, respectively, with demand number of channels (DN) as 1, 2, 4, 6 and 8, respectively.

For $FDM - FDMA$ technique, the simulation is performed with values of each of the primary and secondary non-overlapping channels as 500, each, as shown in Fig. 3(a). Thus, C , the total number of channels is 1000. The primary channels are assumed to be uniformly distributed over the whole spectrum. We assume that on an average, 30% of the primary channels are used by primary users for different broadcasting purposes. That is, 150 primary channels are used by different broadcasting purposes and the rest 70% are idle [21], and those 70% will be available for cognitive radio users. For $OFDM - FDMA$ technique, the simulation is performed with values of each of the primary and secondary overlapping channels as 1000 each, because the width of one non-overlapping channel is equal to that of two overlapping channels, as shown in Fig. 3(b). Thus, C , the total number of overlapping channels will be taken as 2000 for the given total communication bandwidth of 1000 non-overlapping channels.

When a cognitive radio user wants to transmit a multimedia signal, the average number of channels blocked by all of its neighbors up to distance two, with different values of range are shown in Table A-2. Note that these values exclude the 150 primary channels used for various broadcasting purposes. From Table A-2, the number of blocked channels by all 2-distance neighbors increases with the sensing and transmission range as expected.

For $FDM - FDMA$ channel allocation technique, Table A-3 shows the values of F_s , F_p and $F = F_p + F_s$ for 500 and 700 nodes, respectively for different values of range used in the simulation experiment. Column 1 of Table A-3 also show the total number of blocked channels, i.e., the channels allocated to all nodes up to 2-distance neighbors of a transmitting node for avoiding the hidden node problem (which are actually taken from Table A-2 corresponding to 500 and 700 nodes, respectively), plus 150 broadcasting channels blocked by primary users. Table A-4, for $OFDM - FDMA$ channel allocation technique, show the values of F_s , F_p and $F = F_p + F_s$ for 700 and 1000 nodes, respectively for different values of range used in the simulation experiment. Column

Table A-4: Average number of free channels for 700 and 1000 nodes in Overlapping Channel

Average number of blocked channels	Average number of free primary channels (F_P)	Average number of free secondary channels (F_S)	Average number of free channels (F)
For 700 nodes			
303	545	640	1185
490	367	431	798
715	210	246	456
961	97	114	211
For 1000 nodes			
379	466	549	1015
647	251	295	546
969	94	111	205
1316	10	11	21

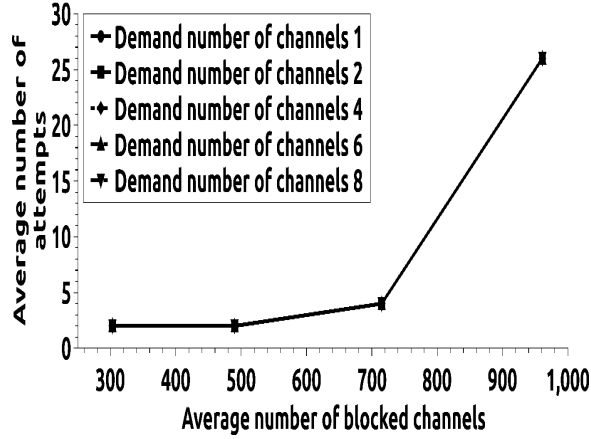


Figure 14: Number of attempts vs percentage of blocked channel for 700 nodes with $FDM - FDMA$

1 of Table A-4 also show the total number of blocked channels, i.e., the channels allocated to all nodes up to 2-distance neighbors of a transmitting node for avoiding the hidden node problem (which are actually taken from Table A-2 corresponding to 700 and 1000 nodes, respectively). We notice from Table A-4 that the total number of free channels F is much less than the difference between the total number of channels (which is 1000 in our case) and the number of blocked channels given in column 1 of these corresponding Table A-4. This is because of the fact that for avoiding channel interferences between two distinct pairs of communicating nodes, we maintain a gap of one channel on either side of a channel allocated to a communicating pair of nodes for computing the number of free channels to be allocated to other users. From Table A-4, we see that with 700 nodes, the number of free channels can go down to 211, i.e., 10.55% of the total number of channels for a range of 25 meters. This situation corresponds to a moderate traffic in the network. On the other hand, with 1000 nodes and a range of 25 meters, the number of free channels can go down to as low as only 21, which corresponds to a very heavy traffic in the network.

The average number of attempts for different values of DN (corresponding to different multimedia signal types) with different percentage values of blocked channels for 500 and 700 nodes for $FDM - FDMA$ channel allocation technique and 700 and 1000 nodes for $OFDM - FDMA$ channel allocation technique are shown in Tables A-8 and A-9, respectively. The values in these tables capture the behavior of our proposed algorithm under different traffic load (*by load we mean the percentage of blocked channels*) ranging from 30% (light load) to more than 95% (extremely heavy load). Both the Tables A-8 and A-9 show that when the number of free channels decreases, the average number of attempts increases, as expected. For $FDM - FDMA$ technique, when the number of blocked channels lies between 30% and 70%, we require only 2 to 4 attempts. However, in the most unlikely situations of an extremely heavy traffic load with about 96% blocked channels, the average number of attempts will be 29 for $DN = 8$, as shown in Table A-8. For $OFDM - FDMA$ technique, when the number of blocked channels lies between 50% and 70%, the average number of attempt will be equal to 2, while with about 90% blocked channels, the algorithm needs at most 4 attempts on an average. For extremely heavy traffic load with about 99% blocked channels, the average number of attempt is equal to 45 for $DN = 8$, as shown in Table A-9. We, however, note that the sensing time per attempts in $OFDM - FDMA$ channel allocation technique is three times more than that in $FDM - FDMA$ channel allocation technique, as already mentioned in Section 3.1.2. We see from Tables A-8 and A-9 that the number of attempts found through simulation agrees well with the theoretical values except when the traffic is extremely heavy, e.g., 96% blocked channels for $FDM - FDMA$ technique and 99% blocked channels for $OFDM - FDMA$ technique. This small deviation may arise due to randomness in the simulation process.

Tables A-8 and A-9 also show the performance comparison of the proposed protocol with the first-fit and best-fit allocation techniques. We see that our proposed protocol is superior to either of them under all traffic situations in respect of average number of attempts as well as the success rate, *where the success rate is defined as the percentage of the cases the protocol in question can successfully allocate channels*. Thus, with $DN = 8$ and traffic load of 70%, our protocol with $FDM - FDMA$ technique requires only 4 attempts as opposed to 500 attempts using first-fit and 638 attempts using best-fit allocations. Similarly, with $DN = 8$ and traffic load of 70%, our protocol with $OFDM - FDMA$ technique requires only 2 attempts as opposed to 250 attempts using

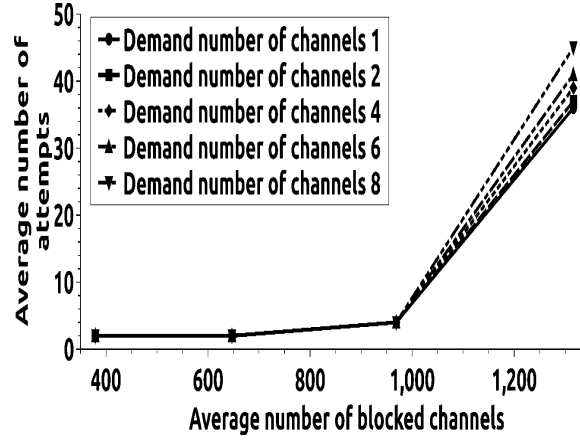


Figure 15: Number of attempts vs percentage of blocked channel for 1000 nodes with *OFDM - FDMA*

Table A-5: Comparison of *FDM - FDMA* and *OFDM - FDMA* for different types of multimedia signal with different nodes and range 25 meter

Number of nodes	Success rate in <i>FDM - FDMA</i>					Success rate in <i>OFDM - FDMA</i>				
	Demand Number of channels					Demand Number of channels				
	8	6	4	2	1	8	6	4	2	1
100 nodes	100	100	100	100	100	100	100	100	100	100
200 nodes	100	100	100	100	100	100	100	100	100	100
300 nodes	100	100	100	100	100	100	100	100	100	100
400 nodes	100	100	100	100	100	100	100	100	100	100
500 nodes	100	100	100	100	100	100	100	100	100	100
600 nodes	100	100	100	100	100	100	100	100	100	100
700 nodes	100	100	100	100	100	100	100	100	100	100
800 nodes	0	0	0	0	0	100	100	100	100	100
900 nodes	0	0	0	0	0	100	100	100	100	100
1000 nodes	0	0	0	0	0	100	100	100	100	100
1100 nodes	0	0	0	0	0	0	0	0	0	0

first-fit and 639 attempts using best-fit allocations. Further, with $DN = 8$, using *FDM - FDMA* technique, the success rate of our protocol is always 100% even up to a traffic load of 96%, while both the first-fit and best-fit techniques fail to allocate any channel under this condition. Similarly, with $DN = 8$ and a traffic load of 99%, using *OFDM - FDMA* technique, neither of the first-fit and best-fit techniques can allocate the channels, although our proposed protocol has the success rate of 100%. The nature of variation of the simulated values of the required number of attempts under different traffic conditions with 700 (for *FDM - FDMA*) and 1000 (for *OFDM - FDMA*) nodes is also shown in Fig. 14 and 15, respectively for different values of DN .

Table A-5 and Fig. 16 show the performance comparison between the *FDM - FDMA* and *OFDM - FDMA* implementations with our protocol. From Table A-5 and Fig. 16, we notice that with a range of 25 meter, *FDM - FDMA* can not allocate the channel beyond 700 nodes, while *OFDM - FDMA* can work satisfactorily even with 1000 nodes.

5.1 Execution Time of the Proposed Protocol

Assuming that the address fields follow *IPv4* (or *IPv6*) format, the maximum length of a message for channel sensing (e.g., *TAM*) will be 10 (or 34) bytes which need 1.25 (or 4) msec with a bandwidth of 64 Kbps for *CCC*. From the data given in Table A-8, we see that for video transmission with about 70% traffic load through eight 64 Kbps channels, four attempts are needed by the Algorithm 3 with *FDM - FDMA* technique, which corresponds to an overhead of $4 \times 8 \times 1.25 \text{ msec} = 40 \text{ msec}$ with *IPv4* format ($4 \times 8 \times 4 = 128 \text{ msec}$ with *IPv6* format). On the other hand, with *OFDM - FDMA* and about 70% blocked channels, Algorithm 5 makes 2 attempts, leading to $2 \times 3 \times 8 \times 1.25 = 60 \text{ msec}$ with *IPv4* format ($2 \times 3 \times 8 \times 4 = 192 \text{ msec}$ with *IPv6* format) for $DN = 8$.

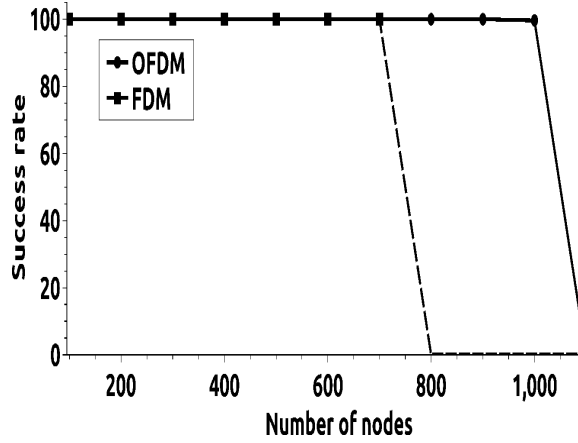


Figure 16: Success rate comparison for $FDM - FDMA$ vs $OFDM - FDMA$ with 8 demand number of channels

5.2 Delay and Delay Jitter in Transmission

In this section, we show our experimental results through simulation by using our proposed scheme on different types of multimedia data. The file categories and the test files have been chosen so as to reflect as closely as possible the different types of wireless data communication that can be seen in today's world. For this purpose, we choose files categorized into four different file types, namely, video, music, image and text. Below we provide a description of files chosen from each of these categories :

1. **Video files** : The video files are in *MPEG* and *DAT* format [18]. Average size of these files is about 48 *MB*.
2. **Music files** : The music files are in *MP3* encoded format [17]. Average size of these files is about 5.87 *MB*.
3. **Image files** : The image files are in *JPEG* format [16]. Average size of these files is about 1.5 *MB*.
4. **Text files** : The text files are in *TXT* file format [11]. Average size of these files is about 80.89 *KB*.

For our experiment with $FDM - FDMA$ technique, we assume a data frame size of 1024 bytes using *IPv4* packet format. We also assume that the channel request and release rates of a user are 0.7 and 0.3, respectively. Each file was tested 1000 times during the simulation to obtain the average delay and delay jitter as reported in the Tables A-10, A-11, A-12 and A-13.

In each of the Tables A-10, A-11, A-12 and A-13, the first column represents the file size. For video transmission we use 8 channels and for music, images and data we use 6, 4 and 2 channels, respectively. The next column represents the average number of channels deallocated by *PUs* when a *PU* asks for its channel currently used by the *SU*. The third column represents ideal transmission (*IT*) time for transmitting files (with zero overhead). The next column represents initial channel allocation (*ICA*) time for grabbing all the required *DN* channels before starting the communication. The fifth column represents channel reallocation (*CR*) time when a *SU* has to deallocate a channel and then a new channel is re-allocated to the *SU*. The, actual transmission (*AT*) time is equal to $IT + ICA + CR$, which is given in the next column. The seventh column represents the maximum possible jitter between two consecutive packets due to channel reallocation. The next column represents the mean jitter and the last column represents the standard deviation of jitter. The appropriate units for the values in different columns have been mentioned in the tables. In each of the above tables, the bold-faced entries in a row represent the average behavior for the corresponding traffic load.

These simulation results show that the overhead in time due to the proposed allocation algorithm constitutes a very small fraction of the total transmission time. For example, from Table A-10, we see that with a traffic load of about 70%, for transmitting video files of size about 48 *MB*, the total transmission time through a 64 *Kbps* channel is around 786.5 sec, while the overhead due to channel allocation and reallocation required by our proposed algorithm is approximately 49 msec ($\approx 0.0062\%$).

During the transmission of the packets, a delay may appear between the transmission of two consecutive data packets whenever a *PU* channel is allocated and that channel is to be released due to the demand from the corresponding *PU*. This delay is due to the execution of our proposed algorithm for reallocating the channels which varies from zero to a finite amount of time, causing delay jitter. We have estimated this delay jitter for all the above cases of our simulation experiment with different types of real-life multimedia data and find that this jitter is very small. For example, from Table A-10, we see that with a traffic load of about 70%, for transmitting video files, the mean jitter is around 0.0015 msec with a standard deviation of about 0.064 msec, whereas the transmission time of a sub-packet of size 1024 bytes through 64 Kbps channel is 125 msec.

6 Analysis of Protocol by Markov Model

To analyze the performance of the proposed protocol for channel allocation and deallocation, we model the system by the Markov's birth and death process, where channel allocation corresponds to the birth process and deallocation corresponds to the death process. At any time instant, the allocation status of the system can be designated by a state $S_k^{k'}$ of the system, where k represents the number of reserved secondary channels and k' represents that of the reserved primary channels. The system will start transmitting the message when all the n required channels are reserved, i.e., $k + k' = n$, and then allocated by the Algorithm 3. At any state $S_k^{k'}$, when a single new (free) channel is reserved by the Algorithm 3, the system can move either to the state $S_k^{k'+1}$ (if the new channel is reserved from the primary band) or to the state $S_{k+1}^{k'}$ (if the new channel is reserved from the secondary band). Similarly, if i channels are reserved in one attempt (Algorithm 3), out of which i_1 channels ($0 \leq i_1 \leq i$), are in the primary band and the rest $i - i_1$ are in the secondary band, then the system will move from the state $S_k^{k'}$ to the state $S_{k+i-i_1}^{k'+i_1}$.

Let μ_1 be the probability per unit time for reserving one new channel in one attempt (either from the primary band or from the secondary band). Then the probability per unit time that the system moves from the state $S_k^{k'}$ to $S_k^{k'+1}$ is given by $\frac{\binom{F_{p,t}}{1}}{\binom{F_t}{1}}\mu_1$ and the probability per unit time that the system moves from the state $S_k^{k'}$ to $S_{k+1}^{k'}$ is given by $\frac{\binom{F_{s,t}}{1}}{\binom{F_t}{1}}\mu_1$. In a similar manner, let μ_2 be the probability per unit time for reserving two new channels in one single attempt. Then the system can move from the state $S_k^{k'}$ to 3 possible states – i) to the state $S_k^{k'+2}$ with a probability of $\frac{\binom{F_{p,t}}{2}}{\binom{F_t}{2}}\mu_2$, ii) to the state $S_{k+2}^{k'}$ with a probability of $\frac{\binom{F_{s,t}}{2}}{\binom{F_t}{2}}\mu_2$, and iii) to the state $S_{k+1}^{k'+1}$ with a probability of $\frac{\binom{F_{p,t}}{1}\binom{F_{s,t}}{1}}{\binom{F_t}{2}}\mu_2$. Similarly, when i channels are reserved in one single attempt, the transition probabilities from the state $S_k^{k'}$ to $i + 1$ different possible states can be expressed in terms of μ_i , the total probability per unit time for reserving i channels, $F_{p,t}$, $F_{s,t}$ and F_t . We assume that the time required for allocating the required number n of channels is small enough so that the values of $F_{p,t}$, $F_{s,t}$ and F_t do not change during the allocation process. Thus, in all the expressions above for transition probabilities, we replace $F_{p,t}$, $F_{s,t}$ and F_t by time-invariant values F_p , F_s and F , respectively. Let λ be the probability per unit time that a grabbed primary channel is released by the system due to the arrival of a channel allocation request from a primary user. For the time being, we assume that only one primary channel may be released at any instant of time. Also, let T be the total time required for completing the communication process of a multimedia message. That means, $\frac{1}{T}$ is the probability per unit time that the system moves from the state S_k^{n-k} , $0 \leq k \leq n$, to the state S_0^0 . Further, let σ be the probability per unit time that the Algorithm 3 terminates unsuccessfully (when all the requested number of channels could not be allocated) after the time-out period.

6.1 1-Channel System

Suppose we want to transmit a voice signal for which $n = 1$. In this case, the system will have only three possible states – i) S_0^0 , when no channel has been reserved, ii) S_0^1 , at which one channel is reserved from the primary band and iii) S_1^0 , at which one channel is reserved from the secondary band. Let p_i^j , ($0 \leq i, j \leq 1$) be the probability that the system is in state S_i^j . The state transition diagram for this system is as shown in Fig. 17. The different transition arcs are labeled with the corresponding probabilities of transition during a small time interval dt . Using

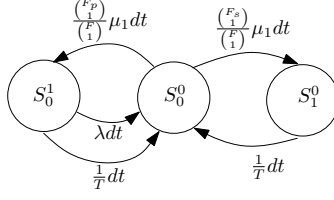


Figure 17: State transition diagram for 1-channel system

the principle of detailed balance for transitions between the states S_0^0 and S_0^1 , we can write,

$$\left(\lambda + \frac{1}{T}\right) p_0^1 = \frac{\binom{F_p}{1}}{\binom{F}{1}} \mu_1 p_0^0 \quad (2)$$

Similarly, for the transitions between the states S_0^0 and S_1^0 , we have,

$$\frac{1}{T} p_1^0 = \frac{\binom{F_s}{1}}{\binom{F}{1}} \mu_1 p_0^0 \quad (3)$$

Since the system must be in one of the three states, we have,

$$p_0^0 + p_1^0 + p_0^1 = 1 \quad (4)$$

Substituting the values of p_0^1 and p_1^0 from eqns. (2) and (3) in eqn. (4), we get,

$$p_0^0 + \left(\frac{\binom{F_p}{1}}{\lambda + \frac{1}{T}}\right) \mu_1 p_0^0 + \left(\frac{\binom{F_s}{1}}{\frac{1}{T}}\right) \mu_1 p_0^0 = 1 \quad (5)$$

That is,

$$p_0^0 = \frac{1}{1 + \left(\frac{\binom{F_p}{1}}{\lambda + \frac{1}{T}}\right) \mu_1 + \left(\frac{\binom{F_s}{1}}{\frac{1}{T}}\right) \mu_1} \quad (6)$$

We say that the system is in the *active* condition when the required numbers of channels are reserved, and the probability for the system being in that condition is given by,

$$P_1 = p_1^0 + p_0^1 = \frac{\left(\frac{\binom{F_p}{1}}{\lambda + \frac{1}{T}}\right) \mu_1 + \left(\frac{\binom{F_s}{1}}{\frac{1}{T}}\right) \mu_1}{1 + \left(\frac{\binom{F_p}{1}}{\lambda + \frac{1}{T}}\right) \mu_1 + \left(\frac{\binom{F_s}{1}}{\frac{1}{T}}\right) \mu_1} \quad (7)$$

We already assume that T is the total time required for completing the communication process of a multimedia message. We also find that the probability for the system being in active state P_1 . So, the average time for communicating the multimedia data is become $\frac{T}{P_1}$. Thus, the average waiting time can be expressed as $\Gamma_1 = T(\frac{1-P_1}{P_1})$.

6.2 2-Channel System

We now consider the case for the 2-channel system for which $n = 2$. As in the case of 1-channel system, we draw the state transition diagram for this system as shown in Fig. 18, consisting of the six states $S_0^0, S_0^1, S_1^0, S_1^1, S_2^0$ and S_2^1 .

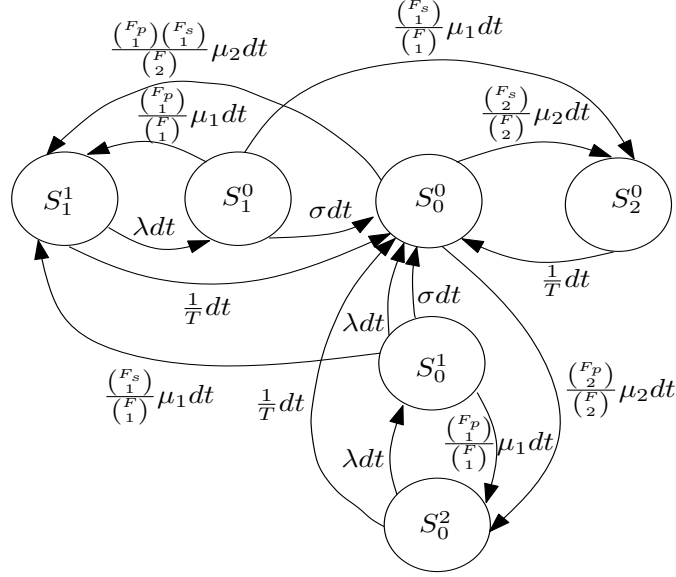


Figure 18: State transition diagram for 2-channel system

Considering all possible transitions to and from the state S_2^0 , we have,

$$\frac{1}{T}p_2^0 = \frac{\binom{F_s}{2}}{\binom{F}{2}}\mu_2p_0^0 + \frac{\binom{F_s}{1}}{\binom{F}{1}}\mu_1p_1^0 \quad (8)$$

Similarly, corresponding to all transitions to and from the state S_0^2 , we have,

$$\left(\lambda + \frac{1}{T}\right)p_0^2 = \frac{\binom{F_p}{2}}{\binom{F}{2}}\mu_2p_0^0 + \frac{\binom{F_p}{1}}{\binom{F}{1}}\mu_1p_1^0 \quad (9)$$

Corresponding to all possible transitions to and from the state S_1^1 , we have,

$$\left(\lambda + \frac{1}{T}\right)p_1^1 = \frac{\binom{F_p}{1}}{\binom{F}{1}}\mu_1p_1^0 + \frac{\binom{F_s}{1}}{\binom{F}{1}}\mu_1p_0^1 + \frac{\binom{F_p}{1}\binom{F_s}{1}}{\binom{F}{2}}\mu_2p_0^0 \quad (10)$$

Considering all possible transitions to and from the state S_0^1 , we get,

$$\left\{\lambda + \sigma + \frac{\binom{F_p}{1}}{\binom{F}{1}}\mu_1 + \frac{\binom{F_s}{1}}{\binom{F}{1}}\mu_1\right\}p_0^1 = \lambda p_0^2 \quad (11)$$

Similarly, considering all possible transitions to and from the state S_1^0 , we get,

$$\left\{\sigma + \frac{\binom{F_p}{1}}{\binom{F}{1}}\mu_1 + \frac{\binom{F_s}{1}}{\binom{F}{1}}\mu_1\right\}p_1^0 = \lambda p_1^1 \quad (12)$$

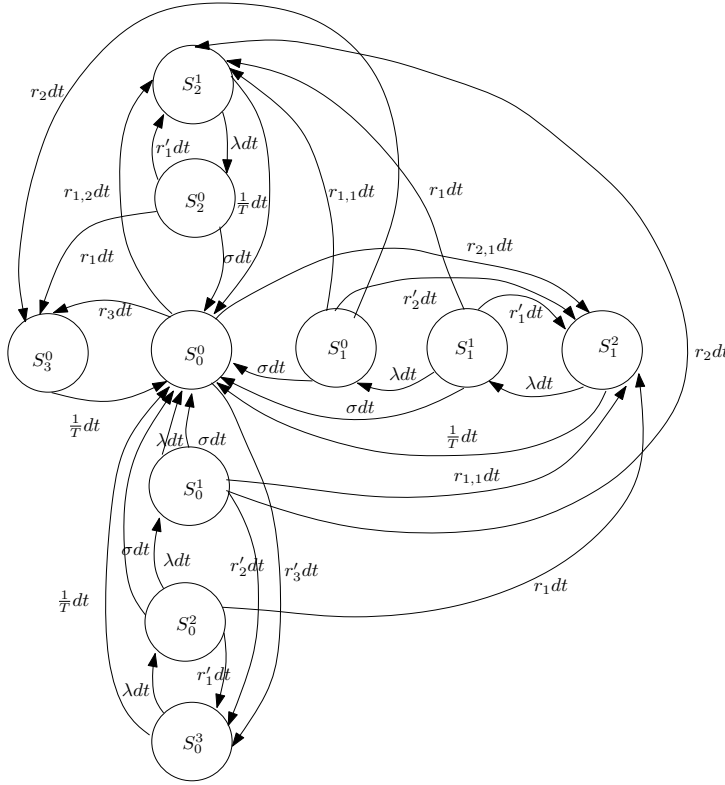
We also have the following condition to be satisfied :

$$p_0^0 + p_1^0 + p_0^1 + p_2^0 + p_0^2 + p_1^1 = 1 \quad (13)$$

The total probability for the system to be in the *active* condition, is given by

$$P_2 = p_2^0 + p_0^2 + p_1^1 \quad (14)$$

Like *1-channel system* we can get the value of P_2 and Γ_2 in terms of λ , σ , μ , T , F_s , F_p and F easily.



$$\begin{aligned}
r_1 &= \frac{\binom{F_s}{1}}{\binom{F}{1}} \mu_1 \\
r'_1 &= \frac{\binom{F_p}{1}}{\binom{F}{1}} \mu_1 \\
r_2 &= \frac{\binom{F_s}{2}}{\binom{F}{2}} \mu_2 \\
r'_2 &= \frac{\binom{F_p}{2}}{\binom{F}{2}} \mu_2 \\
r_3 &= \frac{\binom{F_s}{3}}{\binom{F}{3}} \mu_3 \\
r'_3 &= \frac{\binom{F_p}{3}}{\binom{F}{3}} \mu_3 \\
r_{1,1} &= \frac{\binom{F_p}{1} \binom{F_s}{1}}{\binom{F}{2}} \mu_2 \\
r_{2,1} &= \frac{\binom{F_p}{2} \binom{F_s}{1}}{\binom{F}{3}} \mu_3 \\
r_{1,2} &= \frac{\binom{F_p}{1} \binom{F_s}{2}}{\binom{F}{3}} \mu_3
\end{aligned}$$

Figure 19: State transition diagram for 3-channel system

6.3 3-Channel System

We now consider the case for the 3-channel system for which $n = 3$. As in the case of 1-channel and 2-channel system, we draw the state transition diagram for this system as shown in Fig. 19, consisting of the ten states S_0^0 , S_1^0 , S_2^0 , S_3^0 , S_1^1 , S_2^1 , S_3^1 , S_0^2 , S_1^2 , S_2^2 . The value of r_1 , r'_1 , r_2 , r'_2 , r_3 , r'_3 , $r_{1,1}$, $r_{1,2}$ and $r_{2,1}$ used in the discussion below refer to those given in Fig. 19.

Considering all possible transitions to and from the state S_2^0 , we have,

$$\{\sigma + r'_1 + r_1\} p_2^0 = \lambda p_2^1 \quad (15)$$

Similarly, considering all possible transitions to and from the state S_0^2 , we have,

$$\{\sigma + \lambda + r'_1 + r_1\} p_0^2 = \lambda p_0^3 \quad (16)$$

Considering all possible transitions to and from the state S_1^1 , we get,

$$\{\sigma + \lambda + r'_1 + r_1\} p_1^1 = \lambda p_1^2 \quad (17)$$

Considering all possible transitions to and from the state S_0^1 , we have,

$$\{\sigma + \lambda + r'_2 + r_2 + r_{1,1}\} p_0^1 = \lambda p_0^2 \quad (18)$$

Considering all possible transitions to and from the state S_1^0 , we get,

$$\{\sigma + r'_2 + r_2 + r_{1,1}\} p_1^0 = \lambda p_1^1 \quad (19)$$

Considering all possible transitions to and from the state S_3^0 , we have,

$$\frac{1}{T} p_3^0 = (r_3 p_0^0 + r_1 p_2^0 + r_2 p_1^0) \quad (20)$$

Table A-6: P_n and Γ_n with different message lengths, $F_s = 23$ and $F_p = 16$ for non-overlapped channels with 700 nodes

P_n/Γ_n		$1/T$				
		0.01	0.25	0.5	0.75	0.99
Active State	P_1	0.9769	0.6849	0.5423	0.4517	0.3901
	P_2	0.969	0.6512	0.5172	0.4332	0.3758
	P_3	0.962	0.6282	0.5012	0.4217	0.367
Average Wait- ing Time (in units of T)	Γ_1	2.3692	1.8404	1.6883	1.6183	1.5792
	Γ_2	3.1979	2.1426	1.867	1.7446	1.6778
	Γ_3	3.9501	2.3671	1.9903	1.8287	1.7419

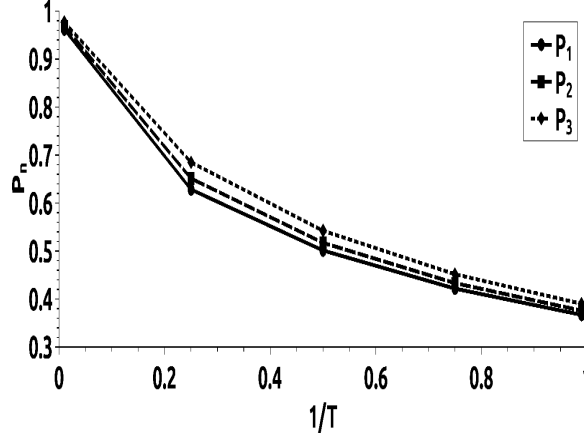


Figure 20: P_n with different lengths of messages for $F_s = 23$ and $F_p = 16$

Considering all possible transitions to and from the state S_0^3 , we get,

$$\left(\lambda + \frac{1}{T}\right) p_0^3 = (r'_3 p_0^0 + r'_2 p_0^1 + r'_1 p_0^2) \quad (21)$$

Considering all possible transitions to and from the state S_2^1 , we have,

$$\left(\lambda + \frac{1}{T}\right) p_2^1 = (r_{1,2} p_0^0 + r'_1 p_2^0 + r_2 p_0^1 + r_1 p_1^1 + r_{1,1} p_1^0) \quad (22)$$

Considering all possible transitions to and from the state S_1^2 , we get,

$$\left(\lambda + \frac{1}{T}\right) p_1^2 = (r'_1 p_1^1 + r'_2 p_1^0 + r_{2,1} p_0^0 + r_{1,1} p_0^1 + r_1 p_0^2) \quad (23)$$

We also have the following condition to be satisfied :

$$p_0^0 + p_1^0 + p_0^1 + p_2^0 + p_0^2 + p_1^1 + p_0^3 + p_0^1 + p_2^1 + p_1^2 = 1 \quad (24)$$

The total probability for the system to be in the *active* condition, is given by

$$P_3 = p_3^0 + p_0^3 + p_2^1 + p_1^2 \quad (25)$$

Like *1-channel system* we can get the value of P_3 in terms of λ , σ , μ , T , F_s , F_p and F easily.

6.4 Examples Showing the Results from Markov Model

In our simulation, we assumed the time-out period to be equal to that corresponding to twice the number of attempts for allocating the required number of channels as predicted by our theoretical estimate. With this time-out period, our algorithm always terminated successfully. Accordingly, we set the value of σ , which is the probability per unit time that the Algorithm 3 terminates unsuccessfully after the time-out period, as equal to zero. For an extremely heavy traffic load of above 96% with 700 nodes using *FDM – FDMA* technique, we use the data

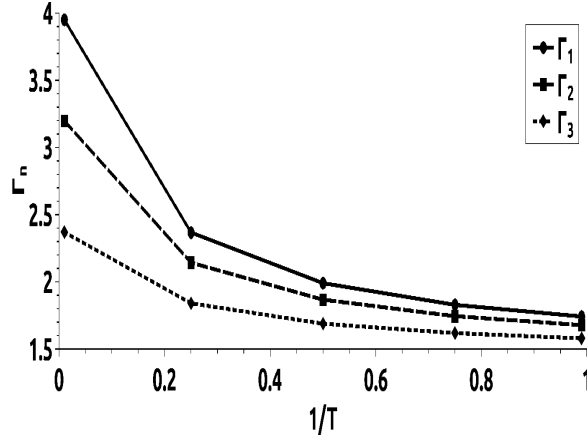


Figure 21: Γ_n with different lengths of messages for $F_s = 23$ and $F_p = 16$

Table A-7: P_n and Γ_n with different message lengths, $F_s = 11$ and $F_p = 10$ for overlapped channels with 1000 nodes

P_n/Γ_n		$1/T$				
		0.01	0.25	0.5	0.75	0.99
Active State	P_1	0.9742	0.6746	0.5349	0.4464	0.386
	P_2	0.9643	0.6374	0.508	0.4266	0.3709
	P_3	0.9555	0.6139	0.4922	0.4155	0.3625
Average Waiting Time (in units of T)	Γ_1	2.6496	1.9298	1.7391	1.6535	1.6065
	Γ_2	3.7059	2.2755	1.9374	1.7918	1.7135
	Γ_3	4.6541	2.5161	2.0633	1.8757	1.7766

taken from Table A-3 with $F_p = 23$ and $F_s = 16$. Assuming $\sigma = 0$, $\lambda = 0.3$ and $\mu_1 = \mu_2 = \mu_3 = 0.7$. The values of both P_n and Γ_n are shown in Tables A-6, for $n = 1, 2, 3$ and for different values of message length. The values of P_n and Γ_n are also shown graphically in Figs. 20 and 21, respectively. From Table A-6, we observe that the probability for the system to be in active condition is more for larger lengths of messages. The value of P_n actually depends on two main factors, *i*) length of the message, and *ii*) channel mobility (which depends on deallocation of a channel when asked by a primary user and then how quickly we get another channel for communication). Thus, under extremely heavy traffic load of above 95%, the probability that the system is in the active condition is effectively dependent only on the length of the message. When the message length is very long, our proposed protocol enables the system to be more than 96% of the time in active condition, while for very short length messages, the system is in active condition for more than 36% of the time. This may be explained by the fact that longer time is needed for transmitting longer messages, and thus the system remains in active condition by grabbing the channel for a larger fraction of time for longer messages.

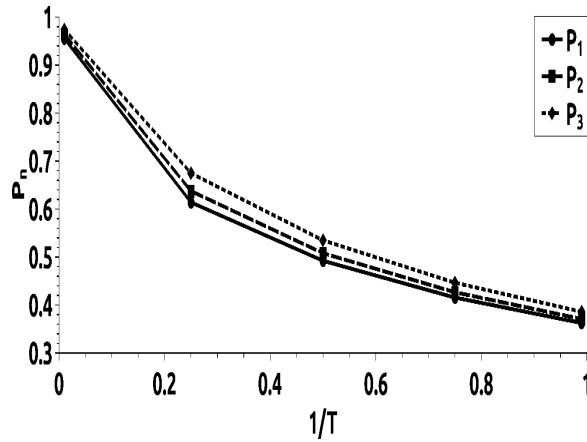


Figure 22: P_n with different lengths of messages for $F_s = 11$ and $F_p = 10$

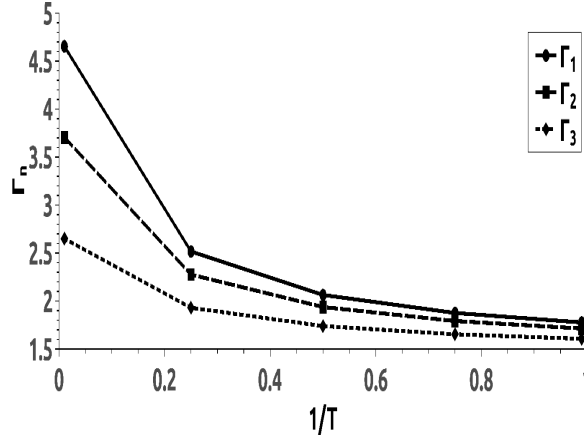


Figure 23: Γ_n with different lengths of messages for $F_s = 11$ and $F_p = 10$

With 1000 nodes using *OFDM – FDMA* technique for $F_s = 11$ and $F_p = 10$, we have similarly computed the values of P_n and Γ_n for $n = 1, 2, 3$ which are shown in Tables A-7. These values of P_n and Γ_n are also plotted in Figs. 22 and 23, respectively.

6.5 Generalization to n-Channel System

To get the value of P_n for any value of n , we need five basic types of states for which the probabilities are given as below.

1. When all reserved channels are secondary :

$$\frac{1}{T}p_n^0 = \sum_{k=1}^n \frac{\binom{F_s}{k}}{\binom{F}{k}} \mu_k p_{n-k}^0 \quad (26)$$

2. When all reserved channels are primary :

$$\left(\lambda + \frac{1}{T}\right) p_0^n = \sum_{k=1}^n \frac{\binom{F_p}{k}}{\binom{F}{k}} \mu_k p_0^{n-k} \quad (27)$$

3. When $k + k' = n$ and $\forall i, 0 < i < n$,

$$\left(\lambda + \frac{1}{T}\right) p_i^{n-i} = \sum_{k=0}^i \sum_{\substack{k'=0 \\ k+k' \leq n}}^{n-i} \left\{ \frac{\binom{F_p}{n-i-k'} \binom{F_s}{i-k}}{\binom{F}{n-k-k'}} \mu_{n-k-k'} p_k^{k'} \right\} \quad (28)$$

4. When $k + k' < n$ and $k' = 0$ (no primary channel is reserved),

$$\left\{ \sigma + \sum_{i=0}^{n-k} \frac{\binom{F_p}{i} \binom{F_s}{n-k-i}}{\binom{F}{n-k}} \mu_{n-k-i} \right\} p_k^0 = \lambda p_k^1 \quad (29)$$

and

5. When $k + k' < n$ and $k' > 0$ (at least one primary channel is reserved),

$$\left\{ \lambda + \sigma + \sum_{i=0}^{n-k-k'} \frac{\binom{F_p}{i} \binom{F_s}{n-k-k'-i}}{\binom{F}{n-k-k'}} \mu_{n-k-k'-i} \right\} p_k^{k'} = \lambda p_k^{k'+1} \quad (30)$$

Since the system must be always in one of the above types of states, we have,

$$\sum_{k=0}^n \sum_{k'=0}^{n-k} p_k^{k'} = 1 \quad (31)$$

When $k + k' = n$, the system will be in *active* state, and the probability for the system being in such a state is given by, $P_n = \sum_{k=0}^{k'=n-k} p_k^{n-k}$. The average waiting time for an $n - \text{channel}$ system can be expressed as $\Gamma_n = T(\frac{1-P_n}{P_n})$.

7 Conclusion

A novel channel allocation technique for multimedia communication in a *CRN* has been presented in this paper. The proposed technique works even when the white spaces in the spectrum do not provide a contiguous bandwidth large enough for maintaining the *QoS* of the multimedia signals. Our technique is based on first finding a set of non-contiguous white spaces whose total width will be equal to the required bandwidth of the multimedia signal. We then sub-divide the bits from the original signal in the time domain, form sub-packets with these subsets of bits and transmit these sub-packets through the set of channels so found. The algorithms for sensing, allocating and deallocating the required channels from the available white spaces taking into account the presence of high-priority primary users have been presented along with the algorithms for transmitting and receiving the data packets with two different implementations using *FDM – FDMA* and *OFDM – FDMA* techniques. The performance of this system has been analyzed by means of a Markov model. Also we find that the average number of attempts for acquiring the required number of channels as obtained from simulation agrees well to the theoretical values for all types of traffic situations ranging from light to extremely heavy (about 96% blocked channels). Simulation results show that the proposed technique always outperforms the existing first-fit and best-fit allocation techniques in terms of the average number of attempts needed for acquiring the necessary number of channels for all traffic situations ranging from light to extremely heavy traffic.

Table A-8: Average number of attempts required for allocating channels for different types of multimedia signal with 500 and 700 nodes in $FDM - FDMA$

Average number of free channels (F)	Demand number of channels (DN)	Our proposed protocol					first-fit protocol				best-fit protocol			
		Number of at-tempts (theoreti-cal value)	Number of at-tempts (simu-lation results)	Number of se-lected primary channels	Number of se-lected secondary channels	Average success rate	Number of at-tempts (simu-lation results)	Number of se-lected primary channels	Number of se-lected secondary channels	Average success rate	Number of at-tempts (simu-lation results)	Number of se-lected primary channels	Number of se-lected secondary channels	Average success rate
For 500 nodes														
746	8	2	2	3	5	100	36	4	4	100	160	4	4	100
	6	2	2	2	4	100	18	3	3	100	88	3	3	100
	4	2	2	2	2	100	8	2	2	100	48	2	2	100
	2	2	2	1	1	100	3	1	1	100	26	1	1	100
	1	2	2	0	1	100	1	0	1	100	19	0	1	100
613	8	2	3	3	5	100	124	4	4	100	315	4	4	100
	6	2	3	2	4	100	45	3	3	100	124	3	3	100
	4	2	3	2	2	100	15	2	2	100	45	2	2	100
	2	2	2	1	1	100	4	1	1	100	16	1	1	100
	1	2	2	0	1	100	1	0	1	100	9	0	1	100
453	8	3	3	3	5	100	430	4	4	62.266	648	4	4	62.266
	6	3	3	2	4	100	199	3	3	99.498	350	3	3	99.498
	4	3	3	2	2	100	40	2	2	100	77	2	2	100
	2	3	3	1	1	100	7	1	1	100	15	1	1	100
	1	3	3	0	1	100	2	0	1	100	6	0	1	100
279	8	4	5	3	5	100	508	4	4	2.441	630	4	4	2.441
	6	4	5	2	4	100	476	3	3	28.429	610	3	3	28.429
	4	4	4	1	3	100	213	2	2	99.136	292	2	2	99.136
	2	4	4	1	1	100	16	1	1	100	23	1	1	100
	1	4	4	0	1	100	3	0	1	100	5	0	1	100
For 700 nodes														
697	8	2	2	3	5	100	55	4	4	100	192	3	5	100
	6	2	2	2	4	100	25	3	3	100	93	2	4	100
	4	2	2	2	2	100	10	2	2	100	44	2	2	100
	2	2	2	1	1	100	3	1	1	100	21	1	1	100
	1	2	2	0	1	100	1	0	1	100	14	0	1	100
510	8	2	3	3	5	100	332	4	4	90.594	570	3	5	90.594
	6	2	3	2	4	100	112	3	3	99.996	230	2	4	99.996
	4	2	3	2	2	100	27	2	2	100	60	2	2	100
	2	2	3	1	1	100	5	1	1	100	14	1	1	100
	1	2	2	0	1	100	1	0	1	100	7	0	1	100
285	8	4	4	3	5	100	500	4	4	2.844	638	3	5	2.844
	6	4	4	2	4	100	474	3	3	31.158	610	3	3	31.158
	4	4	4	2	2	100	200	2	2	99.468	277	1	3	99.468
	2	4	4	1	1	100	15	1	1	100	22	1	1	100
	1	4	4	0	1	100	3	0	1	100	5	0	1	100
39	8	26	29	3	5	100	0	0	0	0	0	0	0	0
	6	26	28	3	3	100	0	0	0	0	0	0	0	0
	4	26	28	2	2	100	494	2	2	0.204	502	2	2	0.204
	2	26	27	1	1	100	391	1	1	78.472	406	1	2	78.472
	1	26	26	0	1	100	25	0	1	100	26	0	1	100

Table A-9: Average number of attempts required for allocating channels for different types of multimedia signal with 700 and 1000 nodes in *OFDM – FDMA*

Average number of free channels (F)	Demand number of channels (DN)	Our proposed protocol					first-fit protocol				best-fit protocol				
		Number of at-tempts (theoreti-cal value)	Number of attempts* (simu-lation results)	Number of se-lected primary channels	Number of se-lected secondary channels	Average success rate	Number of at-tempts (simu-lation results)	Number of se-lected primary channels	Number of se-lected secondary channels	Average success rate	Number of at-tempts (simu-lation results)	Number of se-lected primary channels	Number of se-lected secondary channels	Average success rate	
For 700 nodes															
1185	8	1	2	4	4	100	42	4	4	100	229	4	4	100	
	6	1	2	3	3	100	30	3	3	100	161	3	3	100	
	4	1	2	2	2	100	16	2	2	100	109	2	2	100	
	2	1	2	1	1	100	9	1	1	100	74	1	1	100	
	1	1	2	0	1	100	4	0	1	100	63	0	1	100	
798	8	1	2	4	4	100	94	4	4	100	323	4	4	100	
	6	1	2	3	3	100	52	3	3	100	174	3	3	100	
	4	1	2	2	2	100	25	2	2	100	90	2	2	100	
	2	1	2	1	1	100	12	1	1	100	47	1	1	100	
	1	1	2	0	1	100	5	0	1	100	31	0	1	100	
456	8	2	2	4	4	100	405	4	4	99.473	874	4	4	99.473	
	6	2	2	3	3	100	152	3	3	100	364	3	3	100	
	4	2	2	2	2	100	53	2	2	100	129	2	2	100	
	2	2	2	1	1	100	18	1	1	100	45	1	1	100	
	1	2	2	0	1	100	8	0	1	100	24	0	1	100	
211	8	4	4	4	4	100	946	4	4	34.442	1386	4	4	34.442	
	6	4	4	3	3	100	686	3	3	88.625	1084	3	3	88.625	
	4	4	4	2	2	100	191	2	2	100	343	2	2	100	
	2	4	4	1	1	100	39	1	1	100	70	1	1	100	
	1	4	4	0	0	100	15	0	1	100	29	0	1	100	
For 1000 nodes															
1015	8	1	2	4	4	100	56	4	4	100	242	4	4	100	
	6	1	2	3	3	100	36	3	3	100	154	3	3	100	
	4	1	2	2	2	100	19	2	2	100	93	2	2	100	
	2	1	2	1	1	100	10	1	1	100	57	1	1	100	
	1	1	2	0	0	100	4	0	1	100	43	0	1	100	
546	8	2	2	4	4	100	250	4	4	99.996	639	4	4	99.996	
	6	2	2	3	3	100	104	3	3	100	274	3	3	100	
	4	2	2	2	2	100	41	2	2	100	109	2	2	100	
	2	2	2	1	1	100	16	1	1	100	44	1	1	100	
	1	2	2	0	1	100	7	0	1	100	25	0	1	100	
205	8	4	4	4	4	100	958	4	4	31.828	1388	4	4	31.828	
	6	4	4	3	3	100	707	3	3	86.829	1103	3	3	86.829	
	4	4	4	2	2	100	201	2	2	99.998	358	2	2	99.998	
	2	4	4	1	1	100	40	1	1	100	71	1	1	100	
	1	4	4	0	1	100	15	0	1	100	29	0	1	100	
21	8	32	45	4	4	100	0	0	0	0	0	0	0	0	
	6	32	41	3	3	100	413	3	3	0.1	413	3	3	0.1	
	4	32	39	2	2	100	965	2	2	5.7	1218	2	2	5.7	
	2	32	37	1	1	100	582	1	1	90.3	658	1	1	90.3	
	1	32	36	0	1	100	115	0	1	100	135	0	1	100	

*The sensing time per attempts in *OFDM – FDMA* channel allocation technique is three times more than that in *FDMA – FDMA* channel allocation technique.

Table A-10: Average Delay and Delay Jitter for different real-life Video files

Video File Size (in bits)	Average Number of Channel Deal- location by PUs	Ideal Transmis- sion Time (IT) (in sec)	Initial Channel Allocation Time (ICA) (in msec)	Channel Reallo- cation Time (CR) (in msec)	Actual Trans- mission Time (AT) (in sec) (AT=IT+ICA+CR)	Maximum Jitter (in msec)	Mean Jitter (in msec)	Standard Devia- tion In Jitter (in msec)
Average number of free channels (F) is 697								
387685216	3.901	757.1976875	19.8	5.85375	757.22334125	1.96625	0.000989475	0.038375
389171680	4.053	760.1009375	19.68	6.0525	760.12667	1.94	0.0010191125	0.038625
390823936	4.059	763.328	19.79	6.09375	763.35388375	1.99875	0.00102175	0.039125
393725152	3.891	768.9944375	19.92	5.88375	769.02024125	1.97625	0.000979325	0.03825
399652192	3.973	780.5706875	19.76	5.9975	780.596445	2.01	0.0009833625	0.0385
403520768	4.072	788.1265	19.61	6.22125	788.15233125	2.07625	0.001010275	0.039625
411901408	4.083	804.4949375	19.61	6.155	804.5207025	2.01125	0.0009791625	0.038375
413877088	4.049	808.3536875	19.76	6.07375	808.37952125	1.97875	0.00096165	0.03775
415495232	4.168	811.514125	19.79	6.27875	811.54019375	2.03125	0.0009903375	0.038625
420989536	4.112	822.2451875	19.71	6.1375	822.271035	1.99375	0.0009554	0.03775
402684220.8	4.0361	786.49261875	19.743	6.07475	786.5184365	1.99825	0.000988985	0.0385
Average number of free channels (F) is 510								
387685216	4.026	757.1976875	23.68	6.48625	757.22785375	2.31625	0.0010963875	0.043125
389171680	3.923	760.1009375	24.26	6.3325	760.13153	2.285	0.0010662625	0.042375
390823936	4.011	763.328	24.02	6.4825	763.3585025	2.305	0.0010869375	0.042875
393725152	3.986	768.9944375	24.14	6.51125	769.02508875	2.35625	0.0010837625	0.043125
399652192	4.191	780.5706875	23.93	6.7525	780.60137	2.34625	0.0011071	0.0435
403520768	4.13	788.1265	24.24	6.64625	788.15738625	2.3125	0.0010792875	0.0425
411901408	4.147	804.4949375	23.96	6.675	804.5255725	2.32	0.00106205	0.042375
413877088	4.071	808.3536875	24.18	6.5425	808.38441	2.2825	0.0010358625	0.0415
415495232	4.278	811.514125	24	6.80875	811.54493375	2.3025	0.0010739375	0.042375
420989536	4.139	822.2451875	23.8	6.80375	822.27579125	2.4	0.0010591125	0.042875
402684220.8	4.0902	786.49261875	24.021	6.604125	786.523243875	2.322625	0.001075075	0.0426625
Average number of free channels (F) is 285								
387685216	4.293	757.1976875	39.77	9.4225	757.24688	3.9	0.001625	0.06575
389171680	4.202	760.1009375	39.83	9.1	760.1498675	3.8725	0.0015	0.064125
390823936	4.305	763.328	40.04	9.185	763.377225	3.8	0.0015	0.0635
393725152	4.306	768.9944375	39.41	9.32625	769.04317375	3.92875	0.0015	0.064875
399652192	4.393	780.5706875	40.35	9.3875	780.620425	3.94875	0.0015	0.064375
403520768	4.212	788.1265	39.82	9.16875	788.17548875	3.9225	0.0015	0.063875
411901408	4.409	804.4949375	39.88	9.3675	804.544185	3.81375	0.0015	0.0625
413877088	4.25	808.3536875	39.76	9.2375	808.402685	3.8975	0.0015	0.06275
415495232	4.323	811.514125	40.55	9.25375	811.56392875	3.88	0.0015	0.0625
420989536	4.394	822.2451875	40.11	9.5325	822.29483	4.01125	0.0015	0.06375
402684220.8	4.3087	786.49261875	39.952	9.298125	786.541868875	3.8975	0.0015125	0.0638
Average number of free channels (F) is 39								
387685216	5.169	757.1976875	279.59	70.92625	757.54820375	38.32625	0.012	0.578125
389171680	4.919	760.1009375	281.79	70.46875	760.45319625	38.9775	0.011875	0.581
390823936	4.971	763.328	286.82	69.2	763.68402	37.66625	0.011625	0.564125
393725152	5.074	768.9944375	283.47	70.0275	769.347935	36.8475	0.011625	0.55675
399652192	5.119	780.5706875	288.57	68.0825	780.92734	36.27125	0.011125	0.5405
403520768	5.016	788.1265	282.11	66.82875	788.47543875	36.2325	0.010875	0.534625
411901408	5.083	804.4949375	285.96	70.90625	804.85180375	37.86625	0.01125	0.55925
413877088	5.077	808.3536875	281.94	68.72875	808.70435625	37.84625	0.010875	0.548125
415495232	5.093	811.514125	285.01	67.725	811.86686	36.2175	0.010625	0.528875
420989536	5.16	822.2451875	281.46	68.43625	822.59508375	36.64125	0.010625	0.531625
402684220.8	5.0681	786.49261875	283.672	69.133	786.84542375	37.28925	0.01125	0.5523

Table A-11: Average Delay and Delay Jitter for different real-life Music files

Music File Size (in bits)	Average Number of Channel Deal- location by PUs	Ideal Transmis- sion Time (IT) (in sec)	Initial Channel Allocation Time (ICA) (in msec)	Channel Reallo- cation Time (CR) (in msec)	Actual Trans- mission Time (AT) (in sec) (AT=IT+ICA+CR)	Maximum Jitter (in msec)	Mean Jitter (in msec)	Standard Devia- tion In Jitter (in msec)
Average number of free channels (F) is 697								
48070656	0.745	125.184	14.2575	1.14625	125.19940375	0.8475	0.0011720375	0.03025
48381952	0.785	125.9946666667	14.475	1.22125	126.0103629167	0.9125	0.00123985	0.03225
48382976	0.822	125.9973333333	14.55	1.265	126.0131483333	0.92375	0.00125	0.033
48451864	0.8	126.1767291667	14.3175	1.27125	126.1923179167	0.9475	0.00125	0.0335
48594944	0.787	126.5493333333	14.4825	1.19125	126.5650070833	0.8625	0.0012045	0.030875
48647680	0.824	126.6866666667	14.4375	1.285	126.7023891667	0.93	0.00125	0.03325
49990032	0.785	130.182375	14.4525	1.2275	130.198055	0.885	0.0012058	0.031125
50430976	0.831	131.3306666667	14.3925	1.32	131.3463791667	0.95875	0.00125	0.0335
50432936	0.842	131.3357708333	14.3925	1.33	131.3514933333	0.98375	0.00125	0.034125
51168256	0.899	133.2506666667	14.505	1.375	133.2665466667	0.97125	0.001375	0.034125
49255227.2	0.812	128.2688208333	14.42625	1.26325	128.2845103333	0.92225	0.0012447188	0.0326
Average number of free channels (F) is 510								
48070656	0.921	125.184	17.7375	1.76125	125.20349875	1.32375	0.00175	0.0465
48381952	0.946	125.9946666667	18.12	1.78875	126.0145754167	1.3025	0.001875	0.04575
48382976	0.947	125.9973333333	17.9175	1.87375	126.0171245833	1.3825	0.001875	0.04825
48451864	0.997	126.1767291667	17.9625	1.93875	126.1966304167	1.36875	0.002	0.04875
48594944	0.919	126.5493333333	17.9925	1.79625	126.5691220833	1.30875	0.001875	0.04575
48647680	0.939	126.6866666667	17.7075	1.775	126.7061491667	1.2975	0.00175	0.0455
49990032	0.993	130.182375	17.7	1.87375	130.20194875	1.33625	0.001875	0.04675
50430976	1.006	131.3306666667	17.67	1.865	131.3502016667	1.37	0.001875	0.04725
50432936	0.983	131.3357708333	17.8425	1.8775	131.3554908333	1.31875	0.001875	0.046
51168256	0.99	133.2506666667	17.8125	1.83	133.2703091667	1.3225	0.00175	0.0455
49255227.2	0.9641	128.2688208333	17.84625	1.838	128.2885050833	1.333125	0.00185	0.0466
Average number of free channels (F) is 285								
48070656	1.338	125.184	29.5875	4.1925	125.21778	2.92375	0.00425	0.103375
48381952	1.344	125.9946666667	29.9175	4.015	126.0285991667	2.7925	0.004125	0.0985
48382976	1.365	125.9973333333	29.37	4.1725	126.0308758333	2.92625	0.00425	0.102875
48451864	1.353	126.1767291667	29.2425	4.2225	126.2101941667	2.99375	0.00425	0.104625
48594944	1.345	126.5493333333	29.16	4.1525	126.5826458333	2.9225	0.00425	0.10225
48647680	1.395	126.6866666667	29.7525	4.205	126.7206241667	2.905	0.00425	0.1025
49990032	1.429	130.182375	29.1	4.49	130.215965	3.12875	0.004375	0.108125
50430976	1.432	131.3306666667	29.4225	4.41375	131.3645029167	3.1	0.00425	0.10625
50432936	1.334	131.3357708333	29.79	4.11375	131.3696745833	2.91125	0.004	0.100125
51168256	1.373	133.2506666667	29.1	4.27875	133.2840454167	3.0225	0.004125	0.10275
49255227.2	1.3708	128.2688208333	29.44425	4.225625	128.3024907083	2.962625	0.0042125	0.1031375
Average number of free channels (F) is 39								
48070656	2.811	125.184	208.0425	46.91	125.4389525	29.3175	0.048	1.05175
48381952	2.821	125.9946666667	205.545	48.30125	126.2485129167	30.1775	0.049	1.07725
48382976	2.798	125.9973333333	209.4075	46.585	126.2533258333	29.2625	0.04725	1.042625
48451864	2.695	126.1767291667	209.3625	43.43375	126.4295254167	27.34125	0.044	0.974
48594944	2.794	126.5493333333	210.39	47.80125	126.8075245833	29.93875	0.048375	1.067125
48647680	2.899	126.6866666667	207.0825	46.5275	126.9402766667	29.435	0.047	1.04275
49990032	2.821	130.182375	205.575	48.3425	130.4362925	30.51	0.0475	1.068125
50430976	2.839	131.3306666667	211.38	46.33125	131.5883779167	29.09875	0.045125	1.01725
50432936	2.93	131.3357708333	206.445	47.4175	131.5896333333	29.33375	0.046125	1.029
51168256	2.75	133.2506666667	206.805	45.8925	133.5033641667	27.82375	0.044	0.9795
49255227.2	2.8158	128.2688208333	208.0035	46.75425	128.5235785833	29.223875	0.0466375	1.0349375

Table A-12: Average Delay and Delay Jitter for different real-life Image files

Image File Size (in bits)	Average Number of Channel Deal- location by PUs	Ideal Transmis- sion Time (IT) (in sec)	Initial Channel Allocation Time (ICA) (in msec)	Channel Reallo- cation Time (CR) (in msec)	Actual Trans- mission Time (AT) (in sec) (AT=IT+ICA+CR)	Maximum Jitter (in msec)	Mean Jitter (in msec)	Standard Devia- tion In Jitter (in msec)
Average number of free channels (F) is 697								
12448128	0.23	48.6255	9.235	0.34625	48.63508125	0.325	0.0009111875	0.017
12459888	0.232	48.6714375	9.125	0.385	48.6809475	0.34625	0.0010105	0.018375
12486256	0.199	48.7744375	9.165	0.33125	48.78393375	0.31	0.00086715	0.01625
12596912	0.248	49.2066875	9.275	0.385	49.2163475	0.3475	0.001	0.018375
12650768	0.234	49.4170625	9.215	0.38125	49.42665875	0.3475	0.0009851375	0.01825
12710512	0.221	49.6504375	9.11	0.35375	49.65990125	0.32875	0.000911725	0.017125
12828824	0.24	50.11259375	9.095	0.385	50.12207375	0.345	0.0009821375	0.018
12903144	0.249	50.40290625	9.08	0.4	50.41238625	0.36	0.001015225	0.01875
12927384	0.25	50.49759375	9.22	0.38375	50.5071975	0.35625	0.000971525	0.018375
12996424	0.263	50.76728125	9.19	0.43375	50.776905	0.395	0.001092575	0.0205
12700824	0.2366	49.61259375	9.171	0.3785	49.62214325	0.346125	0.0009747163	0.0181
Average number of free channels (F) is 510								
12448128	0.331	48.6255	11.57	0.7575	48.6378275	0.68875	0.002	0.036375
12459888	0.311	48.6714375	11.755	0.63125	48.68382375	0.57125	0.001625	0.03025
12486256	0.32	48.7744375	11.69	0.68	48.7868075	0.60375	0.00175	0.032
12596912	0.342	49.2066875	11.775	0.72625	49.21918875	0.655	0.001875	0.034375
12650768	0.302	49.4170625	11.905	0.66125	49.42962875	0.59375	0.00175	0.031
12710512	0.309	49.6504375	11.675	0.67125	49.66278375	0.6125	0.00175	0.031875
12828824	0.31	50.11259375	11.93	0.66	50.12518375	0.595	0.001625	0.030875
12903144	0.327	50.40290625	11.655	0.69875	50.41526	0.62125	0.00175	0.032375
12927384	0.306	50.49759375	11.58	0.68375	50.5098575	0.6125	0.00175	0.031875
12996424	0.313	50.76728125	11.75	0.71375	50.779745	0.64625	0.00175	0.033375
12700824	0.3171	49.61259375	11.7285	0.688375	49.625010625	0.62	0.0017625	0.0324375
Average number of free channels (F) is 285								
12448128	0.501	48.6255	19.315	1.72875	48.64654375	1.51375	0.0045	0.0805
12459888	0.464	48.6714375	19.395	1.565	48.6923975	1.335	0.004125	0.071625
12486256	0.44	48.7744375	19.39	1.6675	48.795495	1.48	0.004375	0.078375
12596912	0.497	49.2066875	18.76	1.705	49.2271525	1.4875	0.004375	0.078625
12650768	0.444	49.4170625	19.865	1.6275	49.438555	1.3925	0.00425	0.073875
12710512	0.469	49.6504375	19.665	1.7825	49.671885	1.55375	0.004625	0.0815
12828824	0.511	50.11259375	19.61	1.91625	50.13412	1.695	0.004875	0.08825
12903144	0.524	50.40290625	19.725	1.96875	50.4246	1.69125	0.005	0.0885
12927384	0.471	50.49759375	19.645	1.7075	50.51894625	1.46125	0.004375	0.0765
12996424	0.524	50.76728125	19.48	1.83875	50.7886	1.55125	0.004625	0.081375
12700824	0.4845	49.61259375	19.485	1.75075	49.6338295	1.516125	0.0045125	0.0799125
Average number of free channels (F) is 39								
12448128	1.455	48.6255	137.89	27.355	48.790745	19.87375	0.072	1.10475
12459888	1.429	48.6714375	131.225	27.9175	48.83058	21.2225	0.07325	1.158875
12486256	1.428	48.7744375	135.71	27.91375	48.93806125	21.02	0.073125	1.1525
12596912	1.463	49.2066875	138.17	28.785	49.3736425	20.625	0.07475	1.146125
12650768	1.465	49.4170625	133.615	27.2375	49.577915	20.34	0.070375	1.112375
12710512	1.4	49.6504375	138.69	26.57125	49.81569875	20.06125	0.0685	1.091125
12828824	1.396	50.11259375	136.1	25.3825	50.27407625	18.91625	0.06475	1.02425
12903144	1.419	50.40290625	134.345	26.0275	50.56327875	18.91625	0.066	1.033
12927384	1.501	50.49759375	136.59	27.545	50.66172875	19.88125	0.06975	1.085375
12996424	1.425	50.76728125	136.87	27.82375	50.931975	20.9325	0.070125	1.123125
12700824	1.4381	49.61259375	135.9205	27.255875	49.775770125	20.178875	0.0702625	1.10315

Table A-13: Average Delay and Delay Jitter for different real-life Text files

Data File Size (in bits)	Average Number of Channel Deallocation by PUs	Ideal Transmission Time (IT) (in sec)	Initial Channel Allocation Time (ICA) (in msec)	Channel Reallocation Time (CR) (in msec)	Actual Transmission Time (AT) (in sec) (AT=IT+ICA+CR)	Maximum Jitter (in msec)	Mean Jitter (in msec)	Standard Deviation In Jitter (in msec)
Average number of free channels (F) is 697								
25848	0	0.2019375	3.9925	0	0.20593	0	0	0
29008	0	0.226625	4.1225	0	0.2307475	0	0	0
30752	0	0.24025	4.035	0	0.244285	0	0	0
112920	0.004	0.8821875	4.11	0.00625	0.88630375	0.00625	0.0008928625	0.002375
322448	0.009	2.519125	4.0375	0.015	2.5231775	0.015	0.00075	0.003375
453664	0.014	3.54425	3.915	0.0275	3.5481925	0.0275	0.0009821375	0.00525
564880	0.013	4.413125	3.9925	0.02625	4.41714375	0.02625	0.00075	0.004375
703728	0.018	5.497875	4.0775	0.0275	5.50198	0.0275	0.0006395375	0.00425
1284416	0.029	10.0345	3.9675	0.05125	10.03851875	0.05125	0.0006487375	0.00575
3098904	0.06	24.2101875	3.9575	0.10625	24.21425125	0.105	0.0005592125	0.007625
662656.8	0.0147	5.17700625	4.02075	0.026	5.181053	0.025875	0.0005222488	0.0033
Average number of free channels (F) is 510								
25848	0.003	0.2019375	5.415	0.0075	0.20736	0.0075	0.00375	0.00525
29008	0	0.226625	5.565	0	0.23219	0	0	0
30752	0	0.24025	5.495	0	0.245745	0	0	0
112920	0.003	0.8821875	5.405	0.00625	0.88759875	0.00625	0.0008928625	0.002375
322448	0.008	2.519125	5.505	0.02	2.52465	0.02	0.001	0.0045
453664	0.016	3.54425	5.4275	0.03625	3.54971375	0.03625	0.00125	0.006875
564880	0.012	4.413125	5.6	0.02375	4.41874875	0.02375	0.000678575	0.004
703728	0.03	5.497875	5.4475	0.06375	5.50338625	0.06	0.0015	0.009375
1284416	0.04	10.0345	5.5	0.0975	10.0400975	0.09375	0.001234175	0.01075
3098904	0.076	24.2101875	5.3725	0.1825	24.2157425	0.175	0.000960525	0.012875
662656.8	0.0188	5.17700625	5.47325	0.04375	5.18252325	0.04225	0.0011266138	0.0056
Average number of free channels (F) is 285								
25848	0.002	0.2019375	9.1725	0.00375	0.21111375	0.00375	0.001875	0.002625
29008	0.001	0.226625	9.54	0.00375	0.23616875	0.00375	0.001875	0.002625
30752	0.001	0.24025	9.6875	0.0025	0.24994	0.0025	0.00125	0.00175
112920	0.006	0.8821875	9.2875	0.02125	0.89149625	0.02125	0.003	0.008
322448	0.018	2.519125	9.3875	0.0875	2.5286	0.0875	0.004375	0.019625
453664	0.028	3.54425	9.2975	0.08875	3.55363625	0.0875	0.003125	0.0165
564880	0.036	4.413125	9.7025	0.17125	4.42299875	0.17125	0.004875	0.029
703728	0.038	5.497875	9.495	0.11125	5.50748125	0.11125	0.002625	0.017
1284416	0.057	10.0345	9.5725	0.28125	10.04435375	0.2775	0.003625	0.0315
3098904	0.135	24.2101875	9.2675	0.54625	24.22000125	0.5175	0.002875	0.038125
662656.8	0.0322	5.17700625	9.441	0.13175	5.186579	0.128375	0.00295	0.016675
Average number of free channels (F) is 39								
25848	0.008	0.2019375	65.48	0.22875	0.26764625	0.22875	0.114375	0.16175
29008	0.011	0.226625	66.48	0.3425	0.2934475	0.3425	0.17125	0.242125
30752	0.01	0.24025	63.5325	0.37625	0.30415875	0.37625	0.188125	0.266
112920	0.044	0.8821875	64.85	1.05375	0.94809125	1.05375	0.1505	0.39825
322448	0.13	2.519125	66.66	4.40625	2.59019125	4.33375	0.220375	0.973
453664	0.162	3.54425	65.68	5.44375	3.61537375	5.19125	0.194375	0.994125
564880	0.204	4.413125	66.3075	6.0925	4.485525	5.8725	0.174125	1.001125
703728	0.215	5.497875	66.3075	6.04	5.5702225	5.74125	0.1405	0.884625
1284416	0.358	10.0345	66.82	9.1375	10.1104575	8.3625	0.115625	0.962125
3098904	0.508	24.2101875	66.67	10.94	24.2877975	9.53625	0.057625	0.716625
662656.8	0.165	5.17700625	65.87875	4.406125	5.247291125	4.103875	0.1526875	0.659975

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